Scientific Research Publishing

American Journal of Plant Sciences, 2017, 8, 1721-1749
http://www.scirp.org/journal/ajps
ISSN Online: 2158-2750
ISSN Print: 2158-2742

Temporal and Spatial Factors Affecting the Nature of Genotype x Environment Interaction in Sugarcane (*Saccharum officinarum L.*) under Ethiopian Agro-Climatic Conditions: An Integrated Approach

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How to cite this paper: Ftwi, M., Mekbib, F. and Abraha, E. (2017) Temporal and Spatial Factors Affecting the Nature of Genotype x Environment Interaction in Sugarcane (*Saccharum officinarum L.*) under Ethiopian Agro-Climatic Conditions: An Integrated Approach. *American Journal of Plant Sciences*, **8**, 1721-1749.
https://doi.org/10.4236/ajps.2017.87119

Received: April 8, 2017
Accepted: June 26, 2017
Published: June 29, 2017

Abstract

Analytical approaches are important for identification the causes of Genotype x environment interaction (GEI) in multi-environment trials (MET). The objectives of this investigation were to explore the nature and causes of the GEI in sugarcane under Ethiopian agro ecological conditions. Data of Cane yield, recoverable sucrose% and sugar yield obtained from 13 test environments were subjected to Additive Main and Multiplicative Interaction (AMMI2) for empirical study. For environmental characterization, mean values of twenty seven temporal and spatial factors were subjected to Principal Component Analysis (PCA). Moreover, to identify the environmental factors affecting the patterns of GEI and its components, mean values of these factors were correlated with environment AMMI2 IPCA scores of the yield traits studied. Results of the present study indicated that the GEI accounted for larger variation than the genotypic effects which suggested its importance and complexity. The PCA bi-plot successfully identified the environmental factors that most discriminated the test environments (crop years and locations). The correlation analysis between the environmental factors and environmental AMMI2 IPCA scores adequately identified the environmental factors affecting GEI and its components. Soil organic matter% and soil clay%, pan evaporation at establishment, relative humidity at growth stage and harvesting month were the major factors that substantially affect the GEI interaction patterns in cane yield while maximum relative humidity recorded during the growing season, all temperature regimes recorded during the entire growing season and at dif-

ferent crop stages were the major factors that affect GEI in recoverable sucrose%. Moreover, the pattern of GEI in sugar yield was significantly affected by harvest age, percent of clay in soil, altitude, relative humidity at harvest and pan evaporation at establishment. For efficient environmental selection and networks, genotype evaluations and formulation of appropriate sugarcane breeding strategy, f METs should adopt the inclusion of these environmental factors identified as major factors influencing the patterns of GEI. Moreover, more information will be generated if other physiological and soil moisture stress indices are included in future GEI studies in sugarcane.

Keywords

AMMI Bi-Plots, Environmental Covariates, Genotypes, MET, PCA Bi-Plots, Test Environments

1. Introduction

Sugarcane (*Saccharum officinarum* L.) is an industrial raw material to produce various products for sugar allied industries such as acetic acid, paper, plywood, industrial enzymes and animal feed and as source of renewable energy [1]. It remains the major economic important crop in tropical and sub-tropical countries and its importance has increased in recent years. However, the development of sugarcane, like other crops, is affected by effects of the environment (E), genotype (G) and their interaction (GEI), of which the latter causes significant variation in cultivar performance among different locations [2]. Moreover, the evaluation of genotypes, aside from the stratification of production environments, is fundamental for the study of relations between genotypes and environments (GEI), especially to identify similar response patterns of genotypes in the environments of the experimental network [3]. Moreover, interactions to the target populations of environments as the structuring target populations of environments are relevant if the interaction is repeatable [4].

Study on the causes of GEI has been done in crops such as ryegrass [5], wheat [6], Sorghum [4] and sugarcane [7] [8] [9]. In sugarcane, however, the majority of GEI studies have been empirical in nature, focusing mainly on quantifying GEI, identifying mega-environment and quantifying sources of variation for resource allocation [10]. Such research works, however, do not specifically identify the factors or causes responsible for its existence. Fewer sugarcane studies have focused on the interpretation of GEIs to understand the nature and causes thereof. This may benefit sugarcane improvement initiatives and allow for the exploitation of GEI rather than its avoidance or acceptance and identified site covariates (soil depth, clay percentage, organic matter percentage, nitrogen mineralization category, and total available moisture) and seasonal covariates (time of harvest, age at harvest, average daily heat units, solar radiation, rainfall, evaporation, and water stress indices) [8] [11]. Moreover, understanding about the causes of GEI is essential for the implementation of efficient selection and evalu-

ation networks, important to establish breeding objectives, formulate recommendation domains, contribute to ideotype design, and identify ideal test conditions [12] [13]. Moreover, Ramburan *et al.* [7] [8] [9] suggested research works conducted to identify the environmental factors that are potential to cause the GEI is very important to formulate appropriate sugarcane breeding program and strategies This highlights the importance of integrated studies on GEI in as tools for the design of sugarcane breeding programs. Different approaches have been used to identify the causes of the GEI. The first involves the use of factorial regression models based on two-way GEI tables with concomitant variables which could either be environmental factors, genotypic traits, or combinations thereof [14]. The second strategy involves the correlation of genotypic or environmental scores derived from additive main effects and multiplicative interaction (AMMI) analysis to genotypic or environmental covariates [5].

Recent study on genotype x environment interaction in sugarcane indicated complex interaction exists under Ethiopian agro-climatic conditions [15]. However, the environmental factors that determining the nature and existence of the interaction in sugarcane have not identified yet. This is because no attempts have been made for integrating the environmental factors with empirical data (yield data) to investigate the nature and causes of GEI for the target environments or sugarcane production area in Ethiopia, Based on these limitations, the objectives of this investigation were to explore the nature and magnitude of the GEI, and identify the major environmental (temporal and spatial) factors that potentially influence environmental separations and GEI patterns.

2. Materials and Methods

2.1. Description of the Test Environments

The study was conducted at across Sugar Estates (Wonji, Metahara and Finchaa) and Sugar Projects (Belles and Tendaho). The study was repeated over three crop years (two successive plant cane crop trials plus first ratoon crop trial) for locations Wonji, Metahara, Finchaa and Belles but one plant cane crop was established for Tendaho location. Detail description of each test environments (crop trials) and locations is provided in **Table 1**.

2.2. Description of Sugarcane Genotypes

In this study, forty-nine (49) introduced sugarcane genotypes along with locally grown varieties (**Table 2**) were included and evaluated for cane yield and cane components. Of which, 21 genotypes were introduced from France while 3 and 5 genotypes were introduced from Philippines and Barbados, respectively. 7 genotypes each were introduced from USA and Cuba. The rest of the 6 were the locally grown varieties which had been introduced in to Ethiopia from India, South Africa and Barbados before 50 years. Genotypes other than the initial letter of PG were advanced clones to the final of stages for release as commercial varieties while the genotypes with the initial letter of PG were clones passed the initial evaluation stages in CIRAD (France).

Table 1. Description of test environments (crop trials) and locations.

SN	Test Environments or Crop Trials	Description of test environments			ARF (mm)	AEP (mm)	AT (˚C)
		Code	Crop Season	Soil type			
	First Plant Cane Crop Trials	**C1**	**2013-2014**				
1	First Plant Cane Crop trial at Wonji	C1W		Vertisol			
2	First Plant Cane Crop trial at Finchaa	C1F		Luvisol			
3	First Plant Cane Crop trial at Metahara	C1M		Luvisol			
4	First Plant Cane Crop trial at Belles	C1B		Vertisol			
	Second Plant Cane Crop Trials	**C2**	**2014-2015**				
5	Second Plant Cane Crop trial at Wonji	C2W		Vertisol			
6	Second Plant Cane Crop trial at Finchaa	C2F		Vertisol			
7	Second Plant Cane Crop trial at Metahara	C2M		Vertisol			
8	Second Plant Cane Crop trial at Belles	C2B		Vertisol			
9	Second Plant Cane Crop trial at Tendaho	C2T		Luvisol			
	First Ratoon Crop Trials	**R1**	**2015-2016**				
10	First Ratoon Crop trial at Wonji	R1W		Luvisol			
11	First Ratoon Crop trial at Metahara	R1F		Luvisol			
12	First Ratoon Crop trial at Finchaa	R1M		Luvisol			
13	First Ratoon Crop trial at Belles	R1B		Vertisol			
	Locations						
		Code	Latitude (m.a.s.l)	Alt (m)			
14	Wonji Sugar Estate	W	8˚31'N and 39˚12'E	1540	831	6.6	17.5
15	Finchaa Sugar Estate	F	8˚53'N and 39˚52'E	1500	950	6.8	22.7
16	Metahara Sugar Estate	M	9˚30'N and 10˚00'E	1400	1309	6.9	25.3
17	Belles Sugar Project	B	12˚07'N and 36˚21'E	1300	400	8.5	24.7
18	Tendaho Sugar Project	T	11˚50'N and 41˚3'E	374	200	6	32.5

*C1 = First Plant cane Crop Trial; C2 = Second Plant Cane Crop Trial; R1 = First Ratoon Crop Trial; ARF = Annual Rainfall; AT = Average temperature; AEP = Average pan evaporation; RH = relative humidity; SN = serial number = Abbreviation; Sugar Estate = Old Sugar Factory which is under production; Sugar Project = new project which is under establishment and not started sugar production.

Table 2. Description of sugarcane genotypes used for the study of genotype x environment interaction.

Code	Genotypes (G)	Origin	Code	Genotypes (G)	Origin
1	PSR97 092	PHILSURIN (Philippines)	26	VMC95 212	USA
2	DB70047	WICSCBS (Barbados)	27	NCO-334	South Africa
3	DB66 113	WICSCBS (Barbados)	28	FG03 418	CIRAD (France)
4	FG06 700	CIRAD (France)	29	CO449	India
5	FG06 729	CIRAD (France)	30	FG03 204	CIRAD (France)
6	PSR97 087	Cuba	31	FG02 553	CIRAD (France)
7	PSR97 051	PHILSURIN (Philippines)	32	FG03 103	CIRAD (France)
8	HO95 988	USDA (Louisiana)	33	FG03 318	CIRAD (France)

Continued

9	Cp99 1534	USDA (USA)	34	FG04 708	CIRAD (France)
10	FG04 829	Cirad (France)	35	FG04 705	CIRAD (France)
11	DB71 060	Cirad (France)	36	FG02 551	CIRAD (France)
12	TCP93 4245	USDA (Texas/Canal Point)	37	FG03 173	CIRAD (France)
13	CP001 252	USDA (USA)	38	FG04 187	CIRAD (France)
14	VMC95 173	USA	39	FG03 372	CIRAD (France)
15	FG03 447	CIRAD (France)	40	FG03 214	CIRAD (France)
16	CO 740	India	41	C86-56	Cuba
17	CP99 1894	USDA (USA)	42	SP70-1284	Cuba
18	FG03 425	CIRAD (France)	43	C86-165	PHILSURIN
19	FG05 408	CIRAD (France)	44	B78-505	Barbados
20	FG03 520	CIRAD (France)	45	C132-81	Cuba
21	FG04 754	CIRAD (France)	46	C86-12	Cuba
22	FG04 466	WICSCBS (Barbados)	47	C90-501	Cuba
23	FG03 526	CIRAD (France)	48	B52-298	Barbados
24	Mex54/245	Mexico	49	CO-678	India
25	FG03 396	CIRAD (France)			

*FG = CIRAD/Guadeloupe (FRANCE); PSR = PHILSURIN (Philippines); CP = USDA (Canal Point/Florida), USA; TC = USDA (Texas/Canal Point), USA; HO = USDA (Houma, Louisiana); USA, BD = WICSCBS (Barbados/Guyana); varieties B52-298, MEX 54/245, NCo-334, Co 449, CO-678 and CO-740 are the existing commercial varieties in Ethiopia while B 78505, C132-81, SP 70-1284, C 86-165, C86-12, C90501and C86-56 are introduced from Cuba and are recently commercialized.

2.3. Experimental Design and Layout

The experiment at each location was conducted a 7 × 7 simple lattice square. Plot size for a genotype per replication was 8.7 × 6 meters (52.5 m^2) with four test rows and two guard rows. Moreover, the design contains 7 blocks per replication and each block had an area of 8.7 m (width) × 48 m (length) = 417.6 m^2 and the experimental area per location was 0.78 hectares. Each replication was defined as replication nested in each location because the replications were unique for location and each block was nested within both replications and location. At planting, 18 two budded sets were laid on a furrow with 5 m length and cane was harvested at 17 and 13 months cane age for plant cane and ratoon crops, respectively. All recommended agronomic and cultural practices were uniform to raise the crop across all the sugar estates.

2.4. Data Collection

Spatial or Site Factors: Data for site and seasonal covariates were collected from weather stations located near the research experiments and were used for the characterization of test environments (Table 3). Data of site covariates were collected from the composite sample of 12 soil samples per environment (trial) and parameters of soil sample such as soil type, soil clay% (CS%), and Organic matter% (OM%) of each trial were analyzed at Soil Laboratory of Su-

Table 3. Description of temporal and spatial factors (covariates).

Temporal factors of growing season	Abbr.	Long Year Averages	Abbr.
Maximum Mean Relative Humidity	MXRH	Average Maximum Temperature	AMXT
Minimum Mean Relative Humidity	MIRH	Average Minimum Temperature	AMIT
Mean Relative Humidity	MRH	Average Temperature	AT
Mean Pan Evaporation	EP	Average Maximum Relative Humidity	AMXRH
Maximum Mean Temperature	MXT	Average Minimum Relative Humidity	AMIRH
Minimum Mean Temperature	MIT	Average Relative Humidity	ARH
Mean Temperature	MT	Average Pan Evaporation	AEP
Relative Humidity During Harvesting Month	RHDH	**Spatial Covariates (factors)**	
Temperature During Harvesting Month	TDH	Altitude	ALT
Pan Evaporation During Harvesting Month	EPDH	Clay Soil Percentage	CS%
Temporal factors recorded at different crop Stages		Soil Organic Matter Percentage	OM%
Temperature at Establishment	TET		
Temperature at Growth Stage	TGS		
Relative Humidity at Establishment	RHE		
Relative Humidity at Growth Stage	RHGS		
Pan Evaporation at Establishment	EPE		
Pan Evaporation at Growth Stage	EPGS		
Harvesting Age	AGE		

*Abbr. = Abbreviation.

garcane Research Stations (Wonji, Metahara, Tendaho and Finchaa). Moreover, altitude (ALT) of each location was also included as location covariate.

Temporal or Seasonal Factors: During the growing season of each trial or test environment, mean growing season value of Relative Humidity (MRH), Maximum Relative Humidity (MXRH), Minimum Relative Humidity (MIRH), Pan Evaporation (EP), Maximum Temperature (MXT) (˚C), Minimum Temperature (˚C) (MIT) and Mean Temperature (MT) were recorded. As to the effects of climatic conditions at different stages of the crop, data was recorded at establishment, grand stage and at harvest. Mean Monthly Temperatures at Establishment (ETE), Relative Humidity at Establishment (RHE) and Pan Evaporation at Establishment (EPE) were recorded during the establishment of each test environment.

Furthermore, Mean Monthly Temperatures at Grand Stage (TGS), Relative Humidity at Grand Stage (RHGS) and Pan Evaporation at Grand Stage (EPGS) were recorded at grand stage of each trial (5 month after planting date). Two months before harvesting month, Relative Humidity (RHDH), Temperature (TDH) and Pan Evaporation (EPDH) were recorded. Moreover, long year data (20 years data) of Average Maximum Temperature (AMXT), Minimum Temperature (AMIT), Mean Temperature (AMT), Maximum Relative Humidity (AMXRH), Pan Evaporation (AEP), Minimum Relative Humidity (AMIRH) and Mean Relative Humidity (AMRH) were obtained from long established meteorological stations of each sugar estates. But, only 5 years average data was availa-

ble from newly established meteorological stations of the Sugar Projects (Tendaho and Belles). Harvest age (AGE) was also included as environmental covariate as the plant cane and ratoon crops were harvested at different cane age.

Yield data: adjusted mean data for Cane Yield, Recoverable Sucrose% and Sugar Yield were used for AMMI2 analysis. Data on ratoon crop was recorded in the same plot as first plant cane crop. As the plant cane and ratoon crops were harvested at 17 and 14 months of cane age respectively, data for cane and sugar yield were converted to tons $ha^{-1}m^{-1}$ (tons per hectares per month) to bring the crop types to the same productivity unit.

2.5. Data Analyses

The two-way table of G × E means for cane yield, recoverable sucrose% and sugar yield were analyzed using the AMMI model:

$$Y_{ij} = \mu + g_i + e_j + \Sigma\lambda_k \alpha_{ik} \delta_{jk} + R_{ij} + \varepsilon \quad (1)$$

where Y_{ij} is the value of the ith genotype in the jth environment; μ is the grand mean; g_i is the mean of the ith genotype; ej is the mean of the jth environment; λ_k is the singular value for principal component (PC) axis k; α_{ik} and δ_{jk} are the PC scores for axis k of the ith genotype and jth environment, respectively; R_{ij} is the residual and ε is the error term as suggested by Gauch [16]. AMMI2 biplots were produced to visualize the GxE interactions for cane yield, recoverable sucrose% and sugar yield, and were analyzed using statistical software GENSTAT 17th Edition [17]. AMMI2 biplots are characterized by the projection of the genotype and environment IPCA1 and IPCA2 scores onto a two-dimensional bi-plot. Genotypes and environments are represented by points while the distance from the origin of the bi-plot to these points represents the amount of interaction that is exhibited by the respective genotype or environment. The angles between two genotype vectors correspond to their correlation.

Adjusted mean data were arranged based on the two-way mean tables of genotype x environment (GEI), genotype x location (GxL), genotype x plant cane crop trials (GxP) and genotype x first ratoon crop trials (GxR) interactions. Only AMMI2 bi-plots for cane yield, recoverable sucrose% and sugar yield data arrange in GxE and GxL matrix were constructed. Due to space limitation, data for cane yield and recoverable sucrose% is not provided while data for sugar yield is presented in **Table 4**. Data of site and seasonal covariates (**Table 6**) were subjected to principal component analysis (PCA) based on test environment x covariate, plant cane crop trials x environmental covariates, locations x long year seasonal covariates and first ratoon crop trials x environmental covariate data combinations and analyzed using statistical software GENSTAT 17th Edition [17]. Moreover, environmental IPCA scores obtained from AMMI model for cane yield, recoverable sucrose% and sugar yield were correlated with mean data of environmental covariates using SAS Software (SAS V.9.2). Test environments were represented by alphabet and number codes as presented in **Table 1** while genotypes were represented by code numbers (**Table 2**). Environmental covariates were represented by abbreviated alphabets (**Table 3**).

Table 4. GxE means for sugar yield (tons·ha^{-1}·m^{-1}).

Genotypes (G)		Locations (L)					Environments (E) (Locations x Crop Years)													
							Plant Cane 1 (C1)				Plant Cane 2 (C2)					Ratoon crop (R1)				
CD	Name	W	F	M	B	T	C1W	C1F	C1M	C1B	C2W	C2F	C2M	C2B	C2T	R1W	R1F	R1M	R1B	Mean
1	PSR97 092	1.16	1.67	1.71	1.31	0.3	1.17	1.69	2.19	1.14	1.28	1.35	1.67	1.43	0.3	1.06	1.87	1.3	1.36	1.40
2	DB70047	0.95	1.42	1.36	1.09	0.15	0.99	1.35	1.37	0.75	1.04	1.28	1.22	1.34	0.15	0.85	1.58	1.5	1.19	1.13
3	DB66 113	1.03	1.79	1.42	1.27	0.47	1.53	1.62	1.37	1.25	0.78	1.56	1.33	1.19	0.47	0.73	2.22	1.55	1.36	1.32
4	FG06 700	0.65	1.27	1.26	1.05	0.2	0.62	1.27	1.1	1.17	0.76	0.97	0.91	0.79	0.14	0.58	1.48	1.74	1.18	0.97
5	FG06 729	0.81	1.53	1.34	1.47	0.14	1.12	1.47	1.46	1.74	0.63	1.22	0.99	1.24	0.14	0.72	1.94	1.53	1.44	1.19
6	PSR97 087	0.89	1.59	1.47	1.11	0.39	1	1.56	1.59	1.06	0.72	1.52	1.33	1.06	0.39	0.96	1.5	1.47	1.2	1.19
7	PSR97 051	1.19	1.79	1.48	1.32	0.3	0.93	1.39	1.45	1.2	0.8	1.63	1.5	1.29	0.3	1.15	2.13	1.51	1.48	1.30
8	HO95 988	0.91	1.28	1.34	1.07	0.21	0.84	1.01	1.28	1.19	0.99	1.19	1.32	0.87	0.21	0.9	1.71	1.4	1.16	1.08
9	CP-99 1534	0.61	1.39	1.1	1.18	0.19	0.55	1.34	1.21	0.86	0.52	1.26	0.97	1.52	0.19	0.75	1.63	1.11	1.16	1
10	FG04 829	0.74	1.55	1.46	1.19	0.09	0.67	1.33	1.31	1.12	0.65	1.15	1.22	1.06	0.09	0.93	2.17	1.84	1.38	1.15
11	DB71 060	0.72	1.58	1.54	1.49	0.34	0.76	1.34	1.97	1.49	0.65	1.59	1.31	1.55	0.34	0.74	1.86	1.39	1.43	1.26
12	TCP93 4245	0.8	1.56	1.57	1.23	0.29	0.81	1.38	1.54	1.08	0.9	1.29	1.34	1.28	0.29	0.68	2.01	1.8	1.33	1.22
13	CP001 252	0.82	1.28	1.43	1.29	0.29	0.93	1.28	1.3	1.12	0.71	0.72	1.35	1.35	0.29	1.25	1.64	1.58	1.39	1.14
14	VMC95 173	1.15	1.2	1.35	0.8	0.24	1.22	1.23	1.83	1	1.31	1.07	1.14	0.47	0.24	0.9	1.27	1.15	0.93	1.06
15	FG03 447	0.95	1.38	1.44	1.11	0.29	0.89	1.36	1.69	0.67	0.98	1.22	1.17	1.45	0.29	0.99	1.58	1.45	1.2	1.15
16	CO 740	1.03	1.65	1.57	1.09	0.44	0.62	1.35	1.73	1.18	1.1	1.54	1.45	0.69	0.44	1.15	1.92	1.53	1.4	1.18
17	CP99 1894	0.73	0.91	1.3	0.9	0.27	0.6	1.1	1.13	1.05	1.11	0.58	1.19	0.71	0.27	0.52	1	1.54	0.95	0.89
18	FG03 425	0.88	1.48	1.07	0.83	0.18	0.98	1.46	1.28	0.89	0.82	0.99	0.97	0.6	0.18	0.8	1.96	0.96	1	1
19	FG05 408	0.6	1.27	1.37	1.03	0.25	0.49	1.16	1.44	0.88	0.68	1.01	0.95	0.97	0.25	1.3	1.77	1.73	1.23	1.06
20	FG03 520	1.58	1.57	1.28	1.44	0.57	2.03	1.17	1.32	1.23	0.97	1.57	1.39	1.57	0.47	1.76	1.87	1.19	1.53	1.41
21	FG04 754	0.88	1.63	1.63	1.23	0.32	0.7	1.46	1.61	1.44	1.25	1.71	1.48	0.94	0.32	0.7	1.73	1.84	1.31	1.28
22	FG04 466	1.42	1.58	1.83	1.36	0.47	1.25	1.35	1.69	1.42	1.2	1.62	2.19	1.67	0.45	0.88	1.69	1.61	1.39	1.39
23	FG03 526	0.98	1.39	1.47	1.1	0.38	1.17	1.25	1.52	0.92	0.84	1.44	1.31	1.18	0.38	0.88	1.46	1.54	1.18	1.16
24	Mex54/245	0.93	1.28	1.41	1.08	0.28	0.94	1.25	1.7	0.68	0.98	1.01	1.17	1.38	0.28	0.87	1.6	1.36	1.17	1.09
25	FG03 396	0.93	1.64	1.33	1.32	0.37	1.16	1.51	1.08	1.13	0.75	1.61	1.22	1.46	0.37	0.7	1.87	1.68	1.37	1.23
26	VMC95 212	0.74	1.59	1.44	1.15	0.23	0.72	1.26	1.54	0.89	0.89	1.61	1.66	1.37	0.23	0.85	2.03	1.17	1.2	1.2
27	NCO-334	1	1.35	1.53	1.06	0.25	1.12	0.96	1.87	0.88	0.99	1.33	1.08	1.1	0.25	0.82	1.76	1.67	1.2	1.17
28	FG03 418	1.38	1.73	1.73	1.46	0.71	1.19	1.64	1.74	1.25	1.3	1.83	1.39	1.8	0.71	1.02	1.8	2.04	1.58	1.46
29	CO449	0.72	1.37	1.4	0.86	0.33	0.67	1.13	1.77	0.75	0.79	1.31	1.12	0.81	0.33	0.69	1.57	1.31	1.02	1.04
30	FG03 204	1.05	1.43	1.68	1	0.49	1.42	1.07	1.49	0.85	1.15	1.44	1.51	0.95	0.49	0.55	1.7	2.07	1.19	1.23
31	FG02 553	0.86	1.31	1.36	1.23	0.42	0.55	1.26	1.47	1.1	0.86	1.23	1.3	1.34	0.42	0.96	1.55	1.31	1.26	1.12
32	FG03 103	0.96	1.17	1.75	1.47	0.12	1.05	0.85	1.78	1.32	0.79	1.43	1.57	1.65	0.42	1.05	1.26	1.87	1.44	1.24
33	FG03 318	1.12	1.56	1.35	1.11	0.22	1.25	1.37	1.22	0.86	1.23	1.52	1.01	1.22	0.32	0.7	1.83	1.83	1.25	1.19
34	FG04 708	0.35	0.44	0.44	0.45	0.27	0.42	0.83	1.08	0.66	0.25	1.19	0.76	0.26	0.27	0.85	1.56	1.21	0.81	0.41
35	FG04 705	0.66	1.26	1.38	1.26	0.17	0.63	1.06	1.45	1.2	0.59	1.08	1.34	1.3	0.17	0.72	1.66	1.37	1.28	1.06

Continued

36	FG02 551	0.77	1.54	1.09	1.06	0.22	0.94	1.26	1.19	0.94	0.29	1.39	1.02	1.07	0.22	1.09	1.94	1.1	1.18	1.05
37	FG03 173	0.83	1.4	1.24	1.22	0.35	0.92	1.17	1.3	1.1	0.97	1.37	1.04	1.34	0.35	0.62	1.67	1.33	1.21	1.11
38	FG04 187	1.16	1.64	1.54	1.4	0.38	1.39	1.54	1.31	1.07	1.26	1.87	1.68	1.77	0.38	0.76	2.02	1.45	1.64	1.39
39	FG03 372	1.35	1.46	1.58	1.32	0.35	1.73	1.35	1.58	0.94	1.68	0.96	1.29	1.6	0.35	0.62	2.04	1.87	1.41	1.36
40	FG03 214	0.87	1.24	1.4	0.86	0.08	1.03	1.26	1.81	1.1	0.78	1.08	0.99	0.5	0.08	0.79	1.4	1.41	1	1.02
41	C86-56	0.83	1.6	1.22	1.18	0.56	0.71	1.36	1.3	0.87	1.09	1.42	1.38	1.45	0.56	0.74	2.18	1.44	1.22	1.17
42	SP70-1284	0.78	1.56	1.11	1.16	0.3	0.6	1.28	1.04	1.06	0.9	1.2	1.19	1.19	0.3	0.68	2.01	0.66	1.23	1.03
43	C86-165	0.94	1.58	1.09	1.36	0.27	0.6	1.47	1.03	1.36	0.99	1.43	1.35	1.36	0.27	1.24	1.82	0.9	1.35	1.17
44	B78-505	0.88	1.2	1.55	1.31	0.15	0.92	0.97	1.8	1.49	1.08	1.14	1.07	1.1	0.15	0.67	1.52	1.74	1.33	1.14
45	C132-81	1.03	1.37	1.32	1.06	0.43	0.91	1.11	1.65	1.17	0.99	1.37	1.16	0.81	0.43	1.21	1.6	1.18	1.21	1.13
46	C86-12	0.97	1.64	1.41	1.11	0.57	1.15	1.35	1.54	1.03	0.79	1.76	1.3	1.06	0.57	1.03	1.77	1.35	1.23	1.22
47	C90-501	0.74	1.6	1.59	1.11	0.35	0.61	1.48	1.65	0.9	0.87	1.41	1.68	1.25	0.35	0.8	1.89	1.43	1.2	1.19
48	B52-298	0.64	1.25	1.24	0.97	0.19	0.55	0.84	1.25	0.92	0.92	1.04	1.03	0.93	0.19	0.77	1.38	1.64	1.05	0.97
49	CO-678	0.84	1.36	1.2	0.97	0.18	1.08	1.01	1.36	0.77	0.92	1.38	1.16	1.11	0.18	0.52	1.66	1.09	1.03	1.04
Mean (E)							0.94	1.28	1.48	1.06	0.91	1.32	1.27	1.17	0.3	0.87	1.74	1.46	1.25	1.15
Mean (L)		0.9	1.44	1.39	1.15	0.3														
$LSD_{5\%}$																				
E												0.07								
G												0.14								
GxL			0.19																	
GxE												0.17								

*LSD for environments (E) to be used for the last row; LDS for genotypes to be use for the last column; LSD for GxL is to be used for cell means of W, F, M, B, T columns; LSD for GxE to be used for the cell means of columns under E in the table.

3. Results and Discussion

3.1. The Nature of Genotype x Environment Interactions (GEI): An Empirical Approach

AMMI2 Analysis of Variance

Analysis of variance for additive main effects and multiplicative interaction (AMMI2) of cane yield, recoverable sucrose% and sugar yield data is presented in Table 5. The main (environments and genotypes) and interaction effects were all highly significant for all yield traits. Regarding the relative magnitude of each effect, environment followed by GEI and genotype effect accounted for the largest variation. The same trend was observed for all components of the GEI. The GEI accounted for 21.44%, 29.60%, and 23.84% of total variation for cane yield, recoverable sucrose%, and sugar yield, respectively. However, our results were in opposite to their results of where the variations of yield accounted for GEI were by far greater than the variations accounted for the environmental effect for all yield traits studied. GxL accounted for 10.58%, 21.48% and 12.17% in cane yield, recoverable sucrose% and sugar yield respectively while 26.64%, 28.99%

Table 5. AMMI2 analysis of variance for 49 genotypes evaluated across environments for Cane Yield (tons·ha^{-1}·m^{-1}), Recoverable Sucrose% and Sugar Yield (tons·ha^{-1}·m^{-1}).

Sources of Variation	DF	Cane yield			Recoverable Sucrose%			Sugar Yield		
		SS	%	MS	SS	%	MS	SS	%	MS
Environment (E)	12	8798.2	64.19	733**	1964.4	59.82	163.7**	153.5	65.48	12.40**
Genotypes (G)	48	1969.1	14.37	41**	401.81	10.57	7.23**	30.20	10.68	0.5**
GEI	576	2939.3	21.44	5.1**	1119.2	29.60	1.69**	66.10	23.84	0.09**
IPCA1 (AXIS1)	59	655.5	22.30	11.1**	445.37	40.91	6.74**	15.91	24.07	0.22**
IPCA2 (AXIS2)	57	448.2	15.25	7.86**	154.8	14.22	2.43**	10.70	16.19	0.16**
Residual	460	1806	61.45	3.93*	519	46.37	0.98*	39.49	59.74	0.07*
Error	468	1699		3.63	409.64		0.87	29.79		0.063
Locations (L)	4	4331	75.09	1082.8**	1502	68.36	375.5**	82.99	81.3	20.75**
Genotypes (G)	48	826	14.32	17.1**	223.2	10.16	4.65**	9.94	9.74	0.207**
GxL	192	610	10.58	3.2*	472	21.48	2.46**	9.10	8.92	0.047*
IPCA1 (AXIS1)	51	234	38	4.6*	396.45	84	7.77*	3.04	33.4	0.06*
IPCA2 (AXIS2)	49	171	28	3.5*	30.8	7	0.63ns	2.6	28.6	0.053*
Residuals	92	205	34	2.2ns	44.7	9	0.49	3.46	38	0.038*
Error	180	282.79		1.57	148.69		0.83	4.37		0.024
plant cane crop trials across locations (P)	8	4982	55.2	622.72**	1868	61.47	233.53**	92.05	58.62	5.89**
Genotypes (G)	48	1642	18.18	34.21**	290	9.42	6.05**	24.86	15.83	0.21**
GxP	384	2406	26.64	6.26**	881	28.99	2.29**	40.12	25.55	0.06**
IPCA1 (AXIS1)	55	599.33	24.91	10.90**	456.97	51.87	8.25**	11.35	28.3	0.21**
IPCA2 (AXIS2)	53	505.5	21.01	9.54**	126.16	14.32	2.55**	8.265	20.6	0.16**
Residuals	276	1299.2	54	4.71*	297.87	33.81	1.06*	24.51	38.9	0.08*
Error	324	196.16		2.99	340		1.05	16.15		0.049
First ratoon crop trials across locations (R)	3	2892.1	74.29	964**	178.7	29.95	59.57**	16.49	56.3	5.49**
Genotypes (G)	48	941	24.17	19.6**	196	32.84	4.083**	13.12	20.8	0.27**
GxR	144	1001	25.71	6.954*	222.1	37.21	1.542*	17.73	22.9	0.12*
IPCA1 (AXIS1)	50	590	58.94	11.8*	112.8	50.31	2.26**	7.94	54.7	0.16*
IPCA2 (AXIS2)	48	347	34.66	7.2*	72.1	32.75	1.50**	5.86	37.8	0.12**
Residual	46	64	6.39	1.4	37.2	16.75	0.806	3.94	7.49	0.085
Error	144	729.91		5.07	113.12		0.76	6.88		0.048

** = highly significant at $p < 0.01$; * = significant at $p < 0.05$; ns = nonsignificant; SS = Sum of squares; MS = Mean square error; GxE = Genotype x Environment Interaction; GxP = genotype x plant cane trials; GxL = genotype x location interaction; GxR = genotype x ratoon crop trials interaction; PC1 = First Principal Component; PC2 = Second Principal Component.

and 25.55% of the variation in cane yield, recoverable sucrose% and sugar yield was explained by genotype x Plant cane crop trial interaction.

GxL interaction for ratoon crops accounted for 25.71%, 37.21% and 22.9% of the variation in cane yield, recoverable sucrose% and sugar yield respectively.

Both GEI interaction IPCA1 and IPCA2 axes were significant for the three yield traits though explain the small proportions of the variation of the GxE interactions. The variation of interaction explained by AMMI2 was larger in GxL interaction than for Genotype x Location x Plant cane interaction (GxP) and GEI for all yield traits studied. It suggests the complexity of the interaction was in order of genotype x environment > genotype x plant cane crop trials > genotype x location interaction > genotype x first ratoon crop trial interaction. Moreover, in all hierarchy of the analysis, the variation explained by the GEI was by far greater than the variation explained by genotype effect indicating the possibility of formation of distinct mega environments. Results of the present study were similar to results reported by Ramburan *et al.* [8] in which the interaction effect was greater than the genotype effect.

AMMI2 bi-plots

The AMMI2 biplots were constructed based on different data matrix to see the separation and patterns of environments and genotypes that contributed more to genotype by environment interaction and its components. The magnitude of interactions between genotypes and environments were interpreted by their respective vector direction, where similar directions indicate positive interactions and vice versa as suggested by [16].

AMMI2 bi-plots for Cane Yield (tons $ha^{-1} \cdot m^{-1}$): The AMMI2 Biplot for cane yield based on the GxE data matrix is presented in **Figure 1(a)**. In the present AMMI2 analysis, a test environment was considered as a Location x Crop Year combination which was characterized by varying seasonal and site covariates. The bi-plot illustrated test environments R1M and C2B exhibited substantial deviation along both IPCA1 and IPPCA2, indicating these environments contributed more to the existing complex GxE observed in **Table 5**. Moreover, C1W, C2W and R1F located far from the origin along the IPCA1 while C2T and R1W deviated along with the IPCA2, which suggested their major contribution to GEI. On the contrary, test environments C2F, C2M, C1F, R1B and C1B showed small deviation around the origin and contributed less to the GEI because of their proximity to the bi-plot origin (**Figure 1(a)**). Regarding to the pattern of the, sugarcane genotypes on the AMMI2 bi-plots, some of the genotypes explicitly scattered on the biplots. For example, genotypes namely; 34, 20, 30, 44, 14, 17, 42, 43, 27, 38, 31 and 36 located far from the origin and contributed more to the interaction while the rest genotypes were located near the origin, indicating their least contribution to the interaction. Genotypes 27, 22, 44, 30 and 39 grouped together in the second quadrant showed better adaptability to test environments from Metahara (C1M, C2M and R1M) while 39, 30, 14 and 17 showed great affinity to test environments C1W and C2W conducted at location Wonji. Genotypes 38, 11, 9, 31 42 and 43 are relatively adaptable to most of the environments conducted at locations Finchaa and Belles while those genotypes located around the origin showed yield stability across environments.

The AMMI2 bi-plot for cane yield constructed based on genotype x Plant cane crop trial (GxP) matrix data (figure not presented) accounted for 46.92%

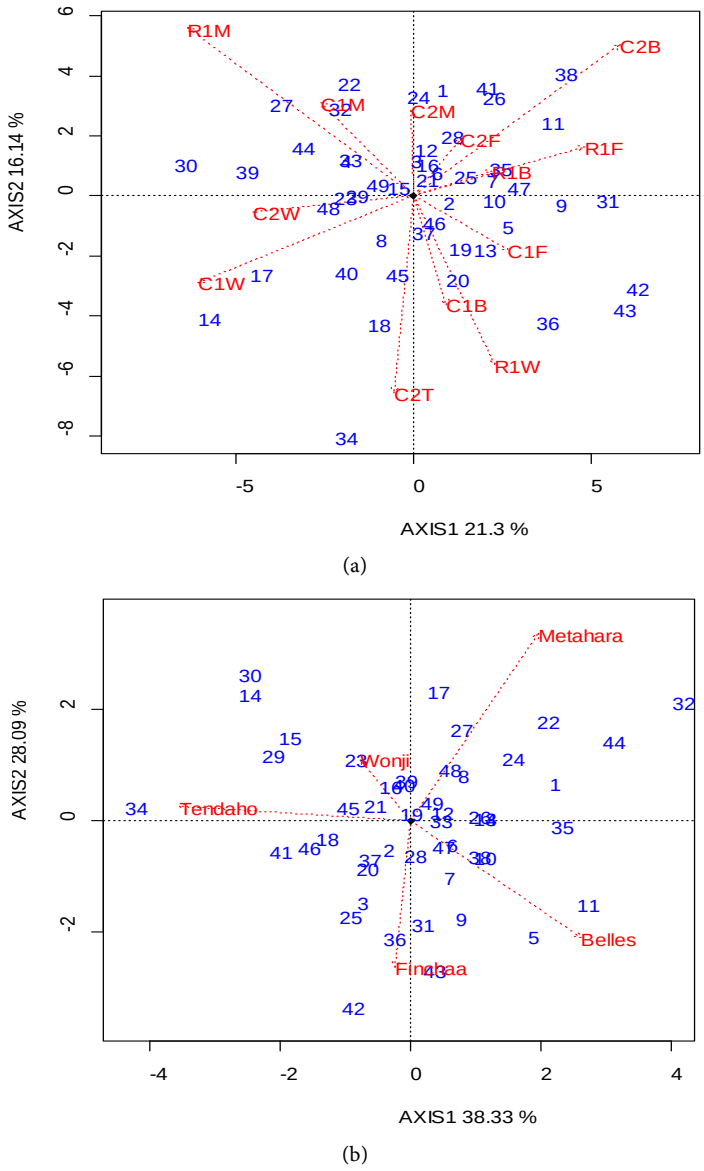
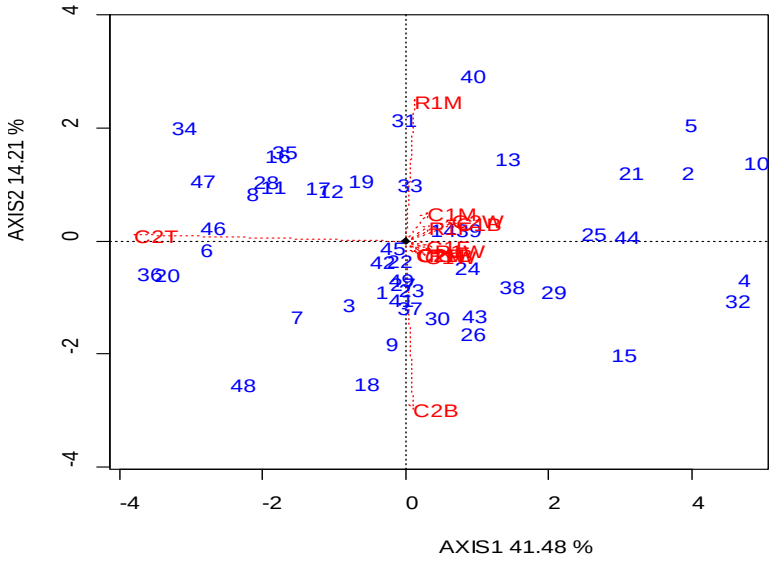


Figure 1. AMMI2 bi-plots for cane yield (a) genotype x environment interaction; (b) GxL interactions; test environments are abbreviated as described in **Table 1**; genotypes are represented with blue clored numbers (1-49) as described in **Table 2**.

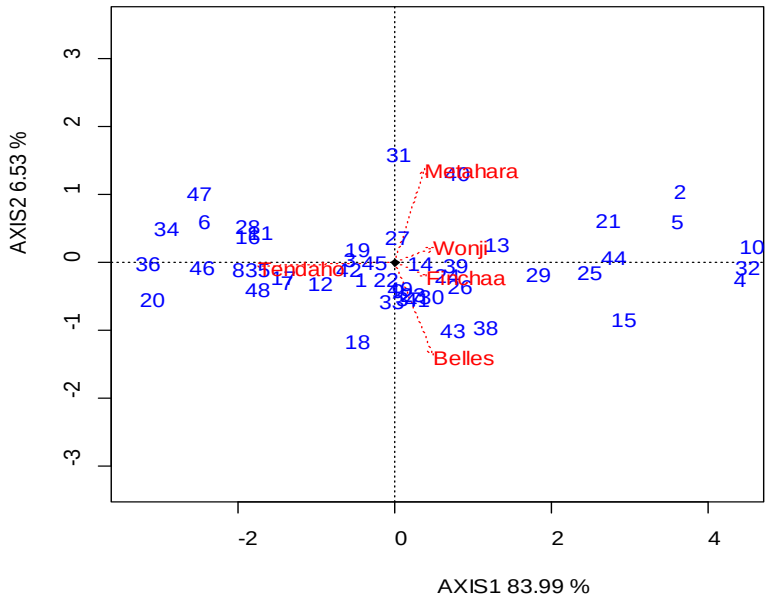
(IPCA1 = 24.91% and IPCA2 = 22.01%). Plant cane trials (C2B, C1W, C2T and C1B) and genotypes (34, 30, 39, 20, 22, 24, 11, 31 and 18) scattered on the bi-plot, suggesting their higher contribution to the large GxP. For locations Wonji and Metahara, plant cane crop trials within a location were more showed substantial overlapping which is an indication of repeatable Genotype x Plant crop cane trials for these locations. The AMMI2 bi-plot based on GxL matrix data for cane yield accounted for 66.42% with first (IPC1 = 38.33%) and second (IPCA2 = 28.09%) axes (**Figure 1(b)**). Locations and genotypes on the AMMI biplots were diverse and scattered on different quadrants, suggesting their higher contribution to the large GxL interaction observed for cane. Moreover, the AMMI2 bi-plot for first ratoon crop trials (figure not presented) accounted for

93.62% (IPCA1 = 58.95, IPCA2 = 34.67%) of the variation due to GxR interaction in cane yield. First ratoon crop trials from Metahara (R1M), Wonji (R1W) and Finchaa (R1F) had long vector length contributed more to the GxR interaction while first ratoon crop from Belles (R1B) contributed the least. Genotypes 20, 34, 32, 4, 38, 3, 38 and 42 scattered far from the origin and contributed more to the GxR interaction.

AMMI2 bi-plots for Recoverable Sucrose%: The AMMI2 bi-plot depicted in Figure 2(a) accounted for 55.13% of the variation due to GEI for recoverable sucrose%. Test environments C2T, R1M and C2B had by far longer vector than



(a)



(b)

Figure 2. AMMI2 bi-plots for recoverable sucrose% (a) genotype x environment interaction (b) GxL interactions; test environments are abbreviated as described in Table 1; genotypes are represented with blue clored numbers (1 - 49) as described in Table 2.

the rest environments, an indication of their higher contribution to the GEI while the rest environments were clustered near the origin and their contribution to GEI was minimal. Moreover, C2T was characterized by large IPCA1 score while R1M and C2B had large IPCA2 scores. Unlike to the bi-plot of cane yield displayed in Figure 1(a), genotypes were more scattered but most of the test environments were clustered together on the bi-plot for recoverable sucrose%; an indication of strong genotype contribution to the GEI. Genotypes 31 and 40 showed better ratoonability at Metahara location while genotypes 18 and 9 were adapted test environment C2B. Genotypes 36, 20, 34, 47, 46 and 6 showed better affinity to C2T and were adaptable to this environment where many environmental factors were imposed at grand stage of the crop and received poor management practices. Genotypes located in the first quadrant accumulate more sucrose content while genotypes located around the origin are adaptable to most of the environments tightly clustered around the origin.

The AMMI2 bi-plot (Figure not shown) recoverable sucrose% accounted for 66.87% (IPC1 = 51.50% and IPCA2 = 15.37%) of genotype x plant cane crop trials interaction. Plant cane trials within location were more correlated at locations Wonji, Metahara and Finchaa, and had small IPCA scores for recoverable sucrose% but plant cane crop trials at location Belles were separated, with large IPCA1 and IPCA 2 respectively, suggesting these locations contributed more to GxL interaction for recoverable sucrose%. Moreover, the GxL interaction was repeatable across successive plant cane crop trials (repeatable genotype x plant cane interaction) except for Belles condition. The AMMI2 bi-plot constructed based on GxL matrix data of recoverable sucrose% and displayed in Figure 2(b) accounted for 91.45% of (IPCA1 = 83.04% and IPCA2 = 8.41%). Locations Wonji, Metahara and Finchaa were more correlated and had small IPCA scores but locations Tendaho and Belles were separated, with large IPCA1 and IPCA2, respectively. The result suggested these locations contributed more to GxL interaction for recoverable sucrose%.

The AMMI2 bi-plot for first ratoon crop trials explained 83.34% (IPCA1 = 50.87, IPCA2 = 32.47%) of the variation due to GxR interaction in recoverable sucrose% (figure not presented). First ratoon crop trials from Metahara (R1M), Wonji (R1W) and Belles (R1B) had long vector length contributed more to the GxR interaction while first ratoon crop from Finchaa (R1F) contributed the least. Genotypes 47, 31, 40, 26, 18, 15 and 30 scattered far from the origin and contributed more to more to the GxR interaction. Generally, compared to cane yield, biplots for recoverable sucrose% accounted more for the variation of GxE and its components, indicating the complexity nature of the genotype x environment interaction was reduced in recoverable sucrose%. Moreover, the environments were tightly grouped (except for C2T, C2B and R1M) while the genotypes were more scattered on the biplots. This suggests recoverable sucrose% was more genetically controlled than cane yield.

AMMI2 bi-plots for Sugar Yield (tons·ha^{-1}·m^{-1}): The bi-plot (Figure 3(a)) accounted for 40.26% of the variation due to GEI for sugar yield. Test environment C1W and C2W showed explicitly deviation along the first axis in the posi-

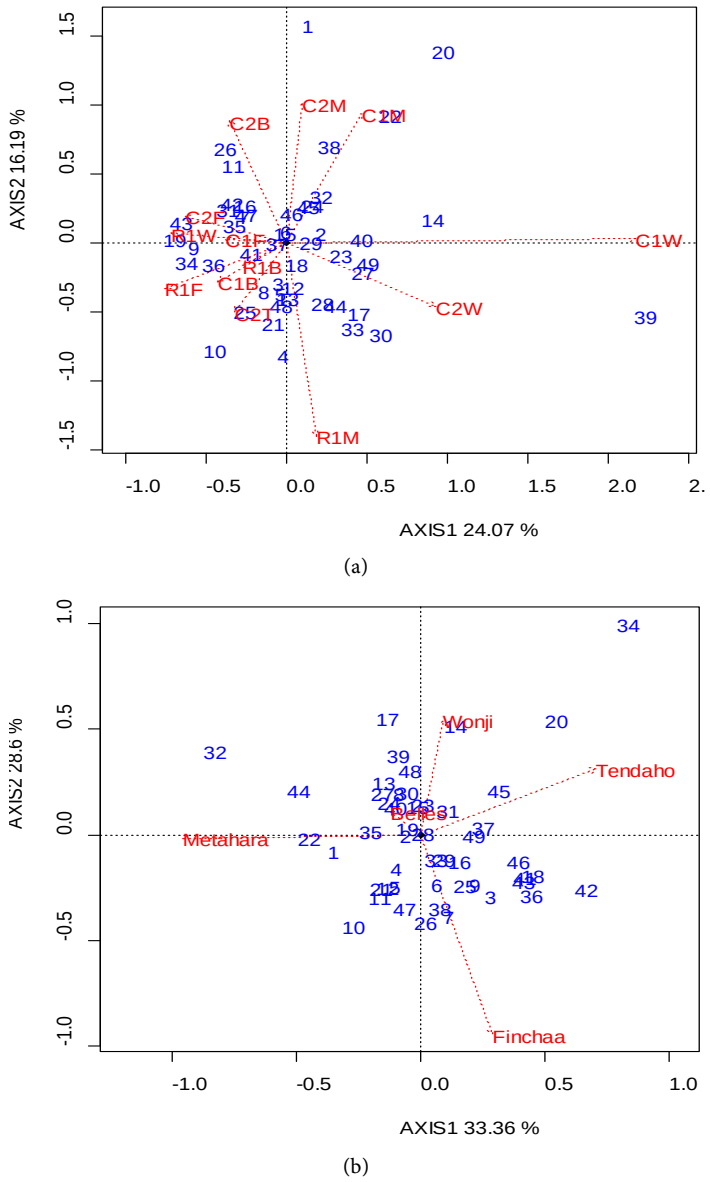


Figure 3. AMMI2 bi-plots for sugar yield (a) genotype x environment interaction (b) GxL interaction; test environments are abbreviated as described in **Table 1**; genotypes are represented with blue clored numbers (1 - 49) as described in **Table 2**.

tive direction while R1F, R1W and C2F located in opposite direction of the same axis. Moreover, test environments R1M, C1M, C2M and C2B showed a clear separation along the second axis. The positions of the above mentioned test environments indicated these environments were more interactive for the existence of genotype x environment interaction in sugar yield. On the contrary, test environments C1F, R1W, C2T and R1B located closer to the origin and their contribution to the GEI was minimal. Regarding to the genotype groupings, sugarcane genotypes 20, 1, 39, 14 and 10 located far from the origin in different quadrants; an indication of their greater share to the interaction in sugar yield. The rest of the genotypes located near the origin and contribute less to the interaction. The AMMI2 bi-plot constructed based on the genotype x plant cane crop

trial interaction (GxP) matrix data of sugar yield (figure not shown) explained 40.02% (IPCA1 = 28.33% and IPCA2 = 20.69%) of the variation due to. Plant cane crop trials (C1W, C2B and C1M) and genotypes (27, 30, 39, 20, 14, 40, 38 and 18) were relatively scattered on the AMMI2 bi-plot. It suggested their major contribution to the complex GxP observed for sugar yield. Plant cane crop trials of the same location were positively correlated (except for plant cane crop trials at Metahara), suggesting GEI was repeatable for plant cane crop trials.

When the data set for sugar yield was arranged based genotype x location matrix, 61.96% of the variation due to GxL interaction was explained by the first two axes (IPC1 = 33.36% and IPCA2 = 28.60%) of AMMI2 bi-plot displayed in **Figure 3(b)**. Locations (Tendaho, Metahara and Finchaa) and genotypes (34, 32, 42, 44, 20, 22, 17, 10, 26, 47, 38, 7, 26, 43 and 8) largely deviated from the origin and scattered on different quadrants. It suggested their substantial contribution to the large GxL interaction in sugar yield. The AMMI2 bi-plot for first ratoon crop trials accounted for 77.8% (IPCA1 = 44.78 IPCA2 = 33.02%) of the variation due to GxR interaction in recoverable sucrose% (figure not presented). First ratoon crop trials from Metahara (R1M), Wonji (R1W) and Belles (R1B) had long vector length and spread more explicitly over the four quadrants. These ratoon trials were predominant in discriminating genotypes differently and inconsistently that favored the existence of GxR interaction (figure not shown). Genotypes 47, 31, 40, 26, 18, 15 and 30 scattered far from the origin and contributed more to more to the GxR interaction. Genotypes 20, 39, 30, 43, 5, 29, 27, 25, 34 and 24 were explicitly scattered on the bi-plot and contributed more to the GxR interaction.

From variety recommendation point of view, Genotypes PRS97 092, FG04 466, FG03 520, FG03 418 and DB66 113 produced higher sugar yield and were stable in wide range of environments (crop years and locations), and can be recommended for commercial purpose in all sugarcane production areas of Ethiopia. Moreover, Genotypes DB71 060 and FG04 187 were specifically adaptable to Finchaa and Belles agro climatic conditions and are recommended are specifically adaptable these production areas while genotype FG03 372 was specifically adaptable to location Wonji and is recommended for commercial purpose for Wonji agro climatic conditions. Generally, the AMMI2 biplots efficiently separated the environments and displayed the patterns of environments and genotypes. Similar to our results, Ramburan *et al.* [7] [8] used AMMI biplots to show clear environmental separations and test genotypes.

3.2. Characterization of Environments Using Temporal and Spatial Factors (Covariates): An Analytical Approach

In the present PCA analysis, three site and twenty four temporal (seasonal) covariates mean values of environments presented in **Table 6** were used. The whole data was arranged on environment x covariate, plant cane trial x covariate, location x covariate and ratoon crop trial x covariate two way data matrices and were analyzed separately. Each data set was subjected to PCA analysis to assess the main differences between the environments, identify the covariates

Table 6. Test environment x covariate two way means data.

Env.	Weather Data Recorded at different Crop Stages													Altitude (m.a.s.l.)
	At Establishment			At Grand Stage				At Harvest						
	TET (˚C)	RHE (%)	EPE (mm)	TGS (˚C)	RHGS (%)	EP GS (mm)	RHDH (mm)	TDH (˚C)	EPDH (mm)	AGE (month)	CS %	OM %	MT (˚C)	
C1W	23.5	69	3.76	18.3	58	5.58	61	25.41	6	17	64	1.78	20	1540
C1F	20.65	67	3.1	22	65.6	4.7	65.6	21.75	4.2	17	35	1.39	22.52	1400
C1M	28.75	44	7.6	24	60.19	6.4	91	23.38	4	17	38	1.21	22.5	950
C1B	25.07	59.7	7.96	22.56	78	4.69	63	24.33	3.8	17	NA	NA	23.89	1128
C2W	22	45	7	16.1	60.8	6	77	22.53	6.5	17	67	2.02	19.2	1540
C2F	24	66.5	4.1	21	74.35	3.4	67.6	21.2	4.7	17	22	3.44	22.32	1400
C2M	26.85	65	7.5	25.7	68	6.2	84.3	24	4.5	17	23	1	22.18	950
C2B	26.31	56.7	6.7	21.95	79.75	3.41	60	23.23	7.6	18	NA	NA	22.8	1128
C2T	36.5	46	5	37	50	2.6	52	40	5.2	17	66	0.66	29.4	374
R1W	18.3	45	6.5	18	46	8	71	19.33	7	14	64	1.78	18.1	1540
R1F	22.35	63.5	4.9	24.95	54	4.1	52.05	22.35	6.2	14	35	1.39	22.38	1400
R1M	21.3	54	6.3	25.95	58	7.2	86.6	23.1	7	14	40	1.21	26.3	950
R1B	24.14	31	12.4	26.2	39.3	6.75	58	22.6	8.4	14	NA	NA	25.3	1128
	Weather Data Recorded during the Growing Season							Long Years (20 years) Weather Data and Altitude						
	MXRH (%)	MIRH (%)	MRH (%)	EP (mm)	MXT (˚C)	MIT (˚C)	MT (˚C)	AMXT (%)	AMIT (˚C)	AMT (˚C)	AMXRH (%)	AMINRH (%)	ARH (%)	AEP (mm)
C1W	86.1	48.7	66.85	6.33	28.3	11.7	20	26.5	8.5	17.5	75.58	33.6	55	6.6
C1F	86.3	40	63.2	4.58	30.4	14.63	22.52	30.66	14.72	22.69	83.82	40.1	62	6.84
C1M	84.3	28	56.15	6.7	33.26	16.6	22.5	33	17.5	25.25	82.2	29.3	56	6.9
C1B*	86.72	49.6	68.16	5.52	30.56	17.22	23.89	NA	NA	24.74	70.3	37.7	54	8.51
C2W	83.6	47.3	65.15	6.31	28.8	9.6	19.2	26.5	8.5	17.5	75.58	33.6	55	6.6
C2F	85.5	40	63	5.05	31	13.64	22.32	30.66	14.72	22.69	83.82	40.1	62	6.84
C2M	81.3	31.3	75	6.8	32.37	17.3	22.18	33	17.5	25.25	82.2	29.3	56	6.9
C2B*	78.33	44.22	61.27	7.23	31.88	13.79	22.8	NA	NA	24.74	70.3	37.7	54	8.51
C2T*	67	51	56	6.5	37	23.2	29.4	40	24.9	32.45	63	54	59	6
R1W	77.5	44.1	60.8	7.5	29.1	6.58	18.1	26.5	8.5	17.5	75.58	33.6	55	6.6
R1F	84.5	30.25	57.37	5.65	31.5	13.25	22.38	30.66	14.72	22.69	83.82	40.1	62	6.84
R1M	84.4	27.5	80	6.97	31.8	17.95	26.3	33	17.5	25.25	82.2	29.3	56	6.9
R1B*	69.44	39.43	54.44	12.2	34.6	16	25.3	NA	NA	24.74	70.3	37.69	54	8.51

*= long year data of 5 years; Env. = Environments; NA = Not Available; CS% = Soil clay%; OM% = Organic matter%; ALT = altitude; MRH = mean growing season value of Relative Humidity; MXRH = Maximum Relative Humidity; MIRH = Minimum Relative Humidity; EP = Pan Evaporation; MXT = Maximum Temperature; MIT = Minimum Temperature; MT = Mean Temperature; ETE = Mean Monthly Temperatures at Establishment; RHE = Relative Humidity at Establishment; EPE = Pan Evaporation at Establishment; TGS = Mean Monthly Temperatures at Grand Stage; RHGS = Relative Humidity at Grand Stage; EPGS = Pan Evaporation at Grand Stage; RHDH = Relative Humidity recorded at harvesting; TDH = Mean Temperature recorded at harvesting; EPDH = Pan Evaporation at harvesting; AMXT = Average Maximum Temperature; AMIT = Average Minimum Temperature; AMT = Average Mean Temperature; AMXRH = Average Maximum Relative Humidity; AEP = Average Pan Evaporation; AMIRH; Average Minimum Relative Humidity; AMRH = Mean Relative Humidity; AGE = Harvest age; Environments are abbreviated as described in Table 1.

driving such differences, and to reveal relationships and redundancies between the covariates. When the whole data set (environment x covariate matrix) was considered, an individual environment was characterized by location x covariate. The PCA bi-plot (Figure 4(a)) constructed based on this data arrangement accounted for 59.38% of the total variation with the first two dimensions (PC1 = 35.81% and PC2 = 23.56%). The explained variation using the first two PC axes was strong enough for correct identification of the covariates that covered high variability to separate the environments and efficiently depict the relationship among environments and environmental covariates.

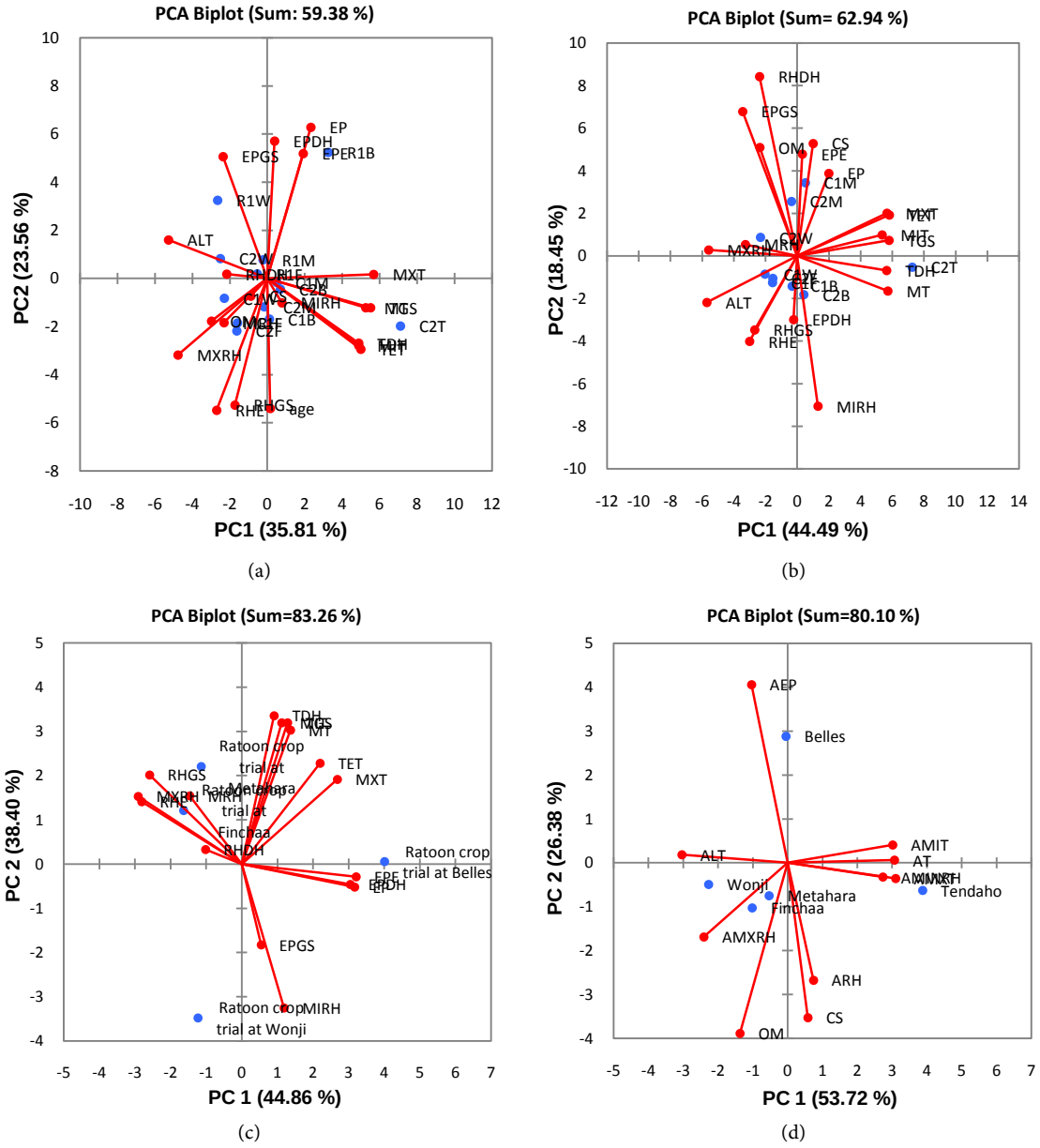


Figure 4. (a) Biplot for characterization based on test environment x Covariate; (b) plant Cane Crop Trials x Environmental Covariates; (c) locations x long year seasonal covariates; (d) locations x long year seasonal covariate combinations. test environments are abbrreviated with red clored codes as described in Table 1 while environmental variable are represented with alphabets as described in Table 3.

Based on the pattern of test environments and environmental covariates depicted in the PCA bi-plot, test environments C1W, C2W and R1W were characterized by high altitude, soil organic matter, RHDH and with lower temperature values (MIT, MT, MXT, ETE, TGS and TDH). On the contrary, test environment C2T was characterized with higher mean temperature regimes and lower altitude as the C2T was positively correlated with all temperature averages and negatively correlated with altitude. This suggests trials from location Wonji were negatively correlated with Tendaho location. The higher altitude difference observed between the two locations could be the determinant factor for the established relationship as climatic conditions are greatly affected by altitude. Test environments C2F and C1F were characterized with higher relative humidity (RHE, MXRH, RHDH, MRH and RH) while test environments from locations Metahara (C1M, C2M) and Belles (C1B and C2B) which showed overlapping were characterized with higher minimum relative humidity (MIRH) while R1B was characterized by higher mean values of EP, EPHDH, and AEP.

Among the seasonal covariates studied, RHE, MXRH, ALT, EPGS, RHGS, AGE, and all temperature and pan evaporation regimes had long vector lengths from the origin and contributed more to the total variation; either one of these covariates could be used in future studies. On the contrary, RHDH, MIRH, MRH, OM% and CS% have short vector length from the origin and located close to origin; showed least effect in discriminating the environments. The trend suggested these covariates contributed more to the total variation explained by the PCA bi-plot and play major role in the characterization of test environments. Ramburan *et al*. [8] [9] reported contradictory result to in their similar study where harvest age was the major environmental covariate in discriminating sugarcane crop trials. Generally, the scattering of environments on all quadrants of the PCA bi-plot indicated the existence of temporal and spatial variations among the environments.

Most of the ratoon crop trials were characterized by higher pan evaporation (EP) which separated them from their respective plant cane crops. The bi-plot illustrated the grouping of plant cane crop trials within a location which suggested the presence of minimal temporal variation over the two successive crop years. The observed temporal variation was, therefore, due to the confounding effect of ratoon crop trials. Consequently, it was be more reasonable if the plant cane and ratoon crop trials were separately characterized. The PCA bi-plot constructed based on plant cane crop trials x covariate two way table data is presented in **Figure 4(b)**. Covariates RHDH, EPGH, MIRH, altitude and all temperature regimes contributed more to the PCA bi-plot. Most of the plant cane crop trials were explicitly scattered around the origin and were least discriminated while plant cane crop conducted at location Tendaho (C2T) was highly discriminated by higher temperature regimes and altitude. Plant cane trials from location Metahara (C1M, C2M) were closely and positively correlated with RHDH, OM%, EPGS and negatively correlated with MIRH. It indicated C1M and C2M were characterized by larger RHDH, OM%, EPGS values and lower

MIRH. Plant cane crop trials from location Wonji (C1W, C2W) were characterized by higher altitude, MXRH and lower temperature regimes. Moreover, relative humidity at establishment (RHE) and growth stage (RHGS) were closely and positively correlated, and were to large extent associated with plant cane crop trials of location Finchaa (C1F, C2F). On the contrary, plant cane crop trial established at Tendaho Sugar Project (C2T) was characterized by higher temperature regimes, and lower altitude and lower maximum relative humidity during the growing season.

Ratoon crop trials were highly discriminated by most of the covariates (Except for RHDH, MRH and EPGS) as presented in **Figure 4(c)**. Ratoon crop trial at belles was characterized by MIRH while ratoon crop trial from Finchaa was characterized by higher value of MRH, HGS, MXRH and RHE. Ratoon crop trial at Metahara was discriminated by higher values of temperature regimes and MRH while ratoon crop trial from location Belles was discriminated by higher EPE, EP and EPDH. PCA bi-plots (**Figure 4(a)** & **Figure 4(b)**) revealed the existence of both temporal and spatial variation. However, long year averages of climatic data were not included. The PCA bi-plot constructed using site covariates and long year climatic averages accounted for 77.5% of the total variation with the first two dimensions. Location Tendaho was characterized by high long year average temperature regimes and AMIRH while location Belles was characterized by average long year pan evaporation. CS% and OM% were negatively correlated with location Belles because these covariates were not analyzed for this location (**Table 6**). Moreover, location Wonji is characterized by higher altitude and lower climatic conditions while locations Metahara and Finchaa were characterized by higher AMXRH, MRH, CS% and OM%. Moreover, locations Metahara and Finchaa were closely correlated and showed greater affinity with OM%, CS% and AMXRH. The PCA biplots indicated the application of multivariate analysis for environmental characterization in sugarcane production environments. Ramburan *et al*. [7] and reported similar results where environments were successfully characterized by PCA biplots using site and seasonal covariates.

3.3. Environmental (Temporal and Spatial) Factors Influencing Patterns of Genotype x Environment Interactions and Their Interpretation: An Integrated Approach

The mean values of the environmental (temporal and spatial) factors arranged on environment, location, plant cane and ratoon crop trial basis were correlated with their respective environmental IPCA scores of cane yield, recoverable sucrose% and sugar yield (**Table 7**). Only those environmental factors that showed significant correlation with IPCA scores were discussed. These significant correlations were interpreted in conjunction with environmental characterization displayed in PCA bi-plots (**Figures 4(a)-(d)**), and environmental separations and positions as depicted in AMMI2 biplots for cane yield (**Figure 1(a)** and **Figure 1(b)**), recoverable sucrose% (**Figure 2(a)** and **Figure 2(b)**) and sugar yield (**Figure 3(a)** and **Figure 3(b)**).

Table 7. Correlations of environmental covariates (factors) with environmental AMMI2 IPCA scores of CYLD ($t \cdot ha^{-1} \cdot m^{-1}$), RS% and SYLD ($t \cdot ha^{-1} \cdot m^{-1}$).

Covariate (factor)	Genotype x Environment Interaction (GEI)						Covariate (factor)	Genotype x Plant Cane Crop Trial Interaction					
	Cane Yield		RS%		Sugar yield			Cane Yield		RS%		Sugar yield	
	IPCA1	IPCA2	IPCA1	IPCA2	IPCA1	IPCA2		IPCA1	IPCA2	IPCA1	IPCA2	IPCA1	IPCA2
AGE	0.02ns	−0.07ns	−0.15ns	0.53*	−0.04ns	0.52*							
ALT	−0.24ns	−0.30ns	0.76**	0.18ns	0.6*	0.19ns		−0.16ns	0.49ns	0.80**	−0.13ns	−0.40ns	0.15ns
CS%	0.52*	−0.47ns	−0.26ns	−0.32ns	0.50*	−0.42ns		0.67*	0.11ns	−0.30ns	−0.08ns	−0.70*	−0.17ns
OM%	0.49*	−0.19ns	0.21ns	−0.27ns	−0.28ns	−0.24ns		0.37ns	0.54ns	−0.24ns	0.11ns	0.14ns	0.20ns
MXRH	0.19ns	−0.07ns	0.70**	−0.19ns	−0.20ns	0.04ns		−0.12ns	0.33ns	−0.93**	−0.26ns	−0.19ns	−0.16ns
MIRH	0.69*	−0.43ns	−0.31ns	0.36ns	0.09ns	−0.43ns		−0.19ns	−0.34ns	−0.36ns	0.015ns	−0.24ns	0.19ns
MRH	0.49*	0.23ns	0.31ns	−0.43ns	−0.47ns	0.11ns		−0.06ns	0.22ns	0.49ns	−0.01ns	0.06ns	0.17ns
EP	0.52*	0.31ns	−0.03ns	0.03ns	0.09ns	0.26ns		0.15ns	0.44ns	−0.19ns	0.50ns	−0.22ns	0.63*
MXT	0.02ns	0.22ns	−0.74**	−0.05ns	0.09ns	0.29ns		0.22ns	−0.46ns	0.83**	0.13ns	0.45ns	−0.33ns
MIT	0.28ns	0.21ns	−0.65*	−0.28ns	−0.18ns	0.27ns		0.12ns	−0.65ns	0.77**	−0.01ns	0.46ns	−0.38ns
MT	0.20ns	0.22ns	−0.71**	−0.31ns	−0.11ns	0.35ns		0.19ns	0.71*	0.87**	0.08ns	0.45ns	−0.08ns
RHDH	0.57*	0.46ns	0.38ns	−0.38ns	0.62*	0.30ns		−0.11ns	0.35ns	−0.60ns	−0.26ns	−0.05ns	0.65ns
TDH	0.24ns	−0.26ns	−0.94**	−0.06ns	−0.16ns	−0.21ns		−0.23ns	−0.49ns	0.95**	−0.08ns	−0.02ns	−0.12ns
EPDH	−0.16ns	0.20ns	0.06ns	0.13ns	0.08ns	−0.06ns		0.21ns	0.52ns	−0.06ns	0.64ns	−0.33ns	0.72*
TET	0.15ns	0.01ns	−0.79**	0.14ns	−0.07ns	−0.08ns		−0.02ns	−0.36ns	0.86**	−0.08ns	−0.16ns	−0.12ns
TGS	0.09ns	0.05ns	−0.84**	−0.21ns	0.03ns	0.22ns		0.20ns	−0.57ns	0.90**	−0.03ns	0.37ns	−0.12ns
RHE	−0.08ns	−0.29ns	0.22ns	0.15ns	0.21ns	−0.35ns		0.28ns	0.25ns	0.36ns	0.10ns	−0.10ns	0.44ns
RHGS	0.51*	0.33ns	0.27ns	0.38ns	0.14ns	0.03ns		0.77*	0.08ns	0.55ns	0.54ns	0.73*	0.56ns
EPE	−0.06ns	0.54*	0.17ns	−0.06ns	−0.07ns	0.53*		0.24ns	−0.05ns	0.21ns	0.18ns	0.29ns	−0.24ns
EPGS	0.53*	0.43ns	0.51*	−0.45ns	−0.43ns	0.29ns		−0.41ns	0.43ns	0.64*	−0.40ns	−0.35ns	−0.46ns
	Genotype x First Ratoon Crop Trial interaction							Genotype x Location interaction					
MXRH	−0.30ns	0.39ns	−0.16ns	0.58ns	−0.03ns	−0.64ns	AMXT	−0.43ns	0.22ns	0.88*	−0.13ns	−0.20ns	0.06ns
MIRH	0.64ns	−0.70ns	0.75ns	−0.20ns	−0.65ns	0.53ns	AMIT	−0.28ns	0.12ns	0.79*	−0.29ns	−0.04ns	0.14ns
MRH	−0.88ns	−0.16ns	−0.54ns	0.84ns	0.15ns	−0.99*	AT	−0.35ns	0.17ns	0.84*	−0.22ns	−0.12ns	−0.11ns
EP	0.01ns	−0.26ns	−0.17ns	−0.56ns	0.31ns	0.49ns	AMXRH	0.55ns	−0.07ns	0.75*	−0.46ns	0.59ns	0.86*
MXT	−0.27ns	0.42ns	−0.68ns	−0.68ns	0.87ns	0.36ns	AMIRH	−0.78ns	−0.22ns	0.90*	−0.25ns	−0.84*	−0.04ns
MIT	−0.76ns	0.52ns	−0.99*	−0.15ns	0.95*	−0.27ns	ARH	−0.43ns	0.41ns	−0.29ns	0.24ns	−0.47ns	0.78ns
MT	−0.77ns	0.44ns	−0.98*	−0.16ns	0.95*	−0.25ns	AEP	0.88*	−0.45ns	−0.59ns	0.60ns	0.38ns	0.09ns
RHDH	−0.77ns	−0.54ns	−0.32ns	0.89ns	−0.11ns	−0.92ns	ALT	0.39ns	−0.39	−0.86*	0.09ns	0.22ns	0.26ns
TDH	−0.63ns	0.69ns	−0.94*	−0.26ns	0.979*	−0.16ns	CS%	−0.39ns	−0.82*	0.45ns	−0.85*	−0.10ns	−0.43ns
EPDH	−0.13ns	−0.37ns	−0.23ns	−0.41ns	0.30ns	0.33ns	OM%	0.44ns	0.79*	−0.26*	0.85*	0.83*	0.40ns
TET	−0.50ns	0.29ns	−0.80ns	−0.45ns	0.88ns	0.11ns							
TGS	−0.54ns	0.70ns	−0.90ns	−0.39ns	0.99**	0.02ns							
RHE	−0.07ns	0.54ns	−0.05ns	0.36ns	−0.03ns	−0.40ns							
RHGS	−0.52ns	0.37ns	−0.37ns	0.62ns	0.13ns	−0.76ns							
EPE	−0.007ns	−0.20ns	−0.22ns	−0.59ns	0.38ns	0.49ns							
EPGS	−0.27ns	−0.95*	0.15ns	0.53ns	−0.42ns	−0.37ns							

** = significant at 1%; * = significant at %; ns = non significant; IPCA1 = First Interaction Principal Component Axis; IPCA2 = Second Interaction Principal Component Axis; RS% = recoverable sucrose percentage; abbreviations; CYLD = Cane yield; SYLD = Sugar yield; CS% = Soil clay%; OM% = Organic matter%; ALT = altitude; MRH = mean growing season value of Relative Humidity; MXRH = Maximum Relative Humidity; MIRH = Minimum Relative Humidity; EP = Pan Evaporation; MXT = Maximum Temperature; MIT = Minimum Temperature; MT = Mean Temperature; ETE = Mean Monthly Temperatures at Establishment; RHE = Relative Humidity at Establishment; EPE = Pan Evaporation at Establishment; TGS = Mean Monthly Temperatures at Grand Stage; RHGS = Relative Humidity at Grand Stage; EPGS = Pan Evaporation at Grand Stage; RHDH = Relative Humidity recorded at harvesting; TDH = Mean Temperature recorded at harvesting; EPDH = Pan Evaporation at harvesting; AMXT = Average Maximum Temperature; AMIT = Average Minimum Temperature; AMT = Average Mean Temperature; AMXRH = Average Maximum Relative Humidity; AEP = Average Pan Evaporation; AMIRH; Average Minimum Relative Humidity; AMRH = Mean Relative Humidity; AGE = Harvest age.

3.3.1. Environmental Factors Affecting Genotype x Environment Interaction (GxE)

Environments C1W, C2W and R1F separated along the first axis (Figure 1(a)) while R1M and C2B showed substantial deviations along both axes. As C2B was characterized by higher MIRH (**Figure 4(a)**), the positive and significant correlation of MIRH and EP with environmental IPCA1 AMMI2 scores of cane yield (**Table 7**) suggested these were the major climatic factors behind the separation of C2B along the first axis. Similar results were demonstrated by Binbol *et al*. [18] and Ramburan *et al*. [8] [11] where pan evaporation and cane yield were positively correlated. This could be attributed to the established internal moisture relation in sugar cane which is a dominant factor in the synthesis and translocation of sugars and higher evaporative demand on sugar cane causes it to expel excess water through evaporation and thus allowing some of the sugar produced to be used for building new tissue as suggested by Ramburan *et al*. [7] [8] [19] and Clements [20]. Covariates RHDH and OM% were positively and significantly correlated with environmental IPCA1 scores of cane yield and were the major environmental factors that separated test environment C1W along the first axis of the AMMI2 bi-plot (**Figure 1(a)**) as C1W was characterized with soils rich in OM% and clay%, and higher values of RHDH (). Moreover, the positive correlation of EPGS with IPCA1 score identif**Figure 4(a)**ied EPGS as the factor deriving for substantial separation of R1M. Our result was inconsistent with findings reported by Ramburan *et al*. [7] where soil parameters (soil OM% and clay %) showed weak affinity to separate test environments.

The significant and positive correlations of EPE with environmental IPCA 2 score of AMMI2 cane yield demonstrated the separation of R1W along the second axis was due to higher pan evaporation during the establishment of the experiment. The result was similar to the reports of Binbol *et al*. [18] where pan evaporation at establishment (R^2 = 0.79**) and grand stage (R^2 = 0.77**) were positively correlated with cane yield productivity. In addition to this, the lower cane yield productivity observed in this trial might be attributed to the lower climatic potential and higher altitude of the trials from this location. Unlike to the present result, pan evaporation was reported as the least seasonal factor in affecting GEI patterns in cane yield [7]. The cause for the lower values of seasonal covariates were related to the high altitude of the location which lead to slower growth rates and these lower productivity can be compensated and improved by longer crop cycles or increasing harvest ages [8] [21].

The affinity of environmental covariates with GEI patterns in recoverable sucrose% were somewhat different from the conclusions drawn about the causes and implications of the GEI interaction patterns in cane yield. Altitude (ALT), MXRH and EPGS were positively and highly significantly correlated with AMMI2 IPCA1 scores of recoverable sucrose% while all temperature regimes were negatively and highly significantly correlated with environmental IPCA 2 scores. These covariates were responsible factors for small deviation of the trials along with the first axis of AMMI2 bi-plot for recoverable sucrose% (**Figure 2(a)**) as the trials from location Wonji were characterized by higher Altitude

(ALT), MXRH, EPGS and lower temperature regimes (**Figure 4(a)**). These results were consistent with reports of Ebrahim *et al*. [22] who suggested altitude contributes more to the physiological stability of sucrose as the lower air temperature promote a decrease in the acid invertase concentration in stalks and an increase in the concentration of neutral invertase, and a consequent increase in the sucrose content of the stalks. Though the plant cane crop trial at location Tendaho was substantially separated along the first axis, it showed least affinity with environmental covariates and was difficult to identify the factors that led to its separation. Harvest age was positively and significantly correlated with environmental IPCA2 scores of recoverable sucrose% which was the major determinant factor for separation of test environments C2B and R1M along with the center line of the AMMI2 bi-plot which were harvested 18 months and 14 months, respectively. It suggested that the harvest ages used for plant cane and ratoon crop trials were sensitive for recoverable sucrose, especially for Metahara and Belles conditions.

Such correlations were in close agreement with results reported by Ramburan *et al*. [8] and Ramburan [21] where harvest showed significant correlation with environmental IPCA scores of recoverable sucrose%. Compared to the situations observed in cane yield and recoverable sucrose%, the possibility of identifying environmental factors influencing the environmental separation and GEI patterns in sugar yield were somewhat relatively complex. Site factors CS% and ALT significantly and positively correlated with IPCA1 (**Figure 3(a)**). These could be the driving forces for explicit separation of environments conducted at location Wonji (C1W and C2W) which were characterized with soils enriched with clay% and located at higher altitude (**Figure 4(a)**). Moreover, pan evaporation at establishment (EPE) showed strong correlation with IPCA2 of sugar yield (**Table 7**), indicating this factor was the major environmental factor that brought the deviation of C1M, C2M, C2B and R1M along the second axis in the AMMI2 bi-plot (**Figure 3(a)**) as higher pan evaporation was recorded during the establishment of these environments (**Figure 4(a)**). However, it was unclear for the significant and strong correlation of RHDH with IPCA1 scores and was difficult to associate its effect with any separation of environments. As the first plant cane and ratoon crop trials from Finchaa were characterized by soil with poor clay% (**Figure 4(a)**), the negative and significant correlation of soil clay% (CS %) with IPCA1 scores of sugar yield indicated the clay% in soil (CS%) was the major factor for separation of these trials along the first axis. Moreover, altitude and harvest age were the major factors for the positioning of test environments (trials) C1B and C1W along the second axis as these environments were harvested at 17 months cane age and were located at higher altitudes. These relationships indicated that harvest age for plant cane crops at Wonji and Belles needs to be increased as the lower sugar yield produced in these trials might be attributed to lower harvest age in relation to its location at higher altitude. Moreover, pan evaporation during establishment was positively and significantly correlated with IPCA2 scores of sugar yield and was another additional factor for separation of C1B along the vertical line of the AMMI2 bi-plot as C1B was

characterized with higher value of EPE (Table 6). Environmental covariates RHGS and CS% were positively and significantly correlated with plant cane crop trials C1W and C2B IPCA1 2 scores of cane yield, respectively (Table 7).

3.3.2. Environmental Factors Affecting the Pattern Genotype x Plant Cane Crop Trial Interactions (GxP)

Plant cane crop trials C1W and C2B were characterized by higher values of seasonal RHGS and CS% as presented in the PCA bi-plot (Figure not presented). Thus, these covariates were the major environmental factors for the separation of C2B and C1W along the first axis of the AMMI2 bi-plot for plant cane crop trials. Moreover, plant cane crop trial IPCA2 scores were positively and significantly correlated with mean temperature of the growing seasons (MT) of the trials. Plant cane crop trials C2T and C1B were characterized by higher mean temperatures during the growing season (Figure 4(b)) and were explicitly separated along the second axis. Hence, the mean temperature during the growing season was one of the major factors that influenced the genotype × plant cane crop trial interactions in cane yield. For recoverable sucrose%, Altitude and MXRH were significantly and negatively correlated with plant cane crop trial IPCA1 scores of AMMI2 for recoverable sucrose% while all temperature regimes and EPGS were positively correlated to IPCA1 scores of this axis. These covariates (temporal factors) were the caused for the explicit separation of plant cane crop trial established at Tendaho (C2T) along the first axis the AMMI2 bi-plot (Figure not presented) as this trial was characterized by higher temperature regimes and lower altitude (Figure 4(b)). PCA bi-plot for recoverable sucrose% identified pan evaporation at harvest (EPDH) as dominant factor in separating the second plant cane crop trial at location Belles (C2B) and locating at the vertical line of the AMMI2 bi-plot (large IPCA2). The rest plant cane crop trials showed small deviation along the first axis and those covariates that showed medium correlations with IPCA1 scores were responsible for these small deviations and clustering of the rest trials. In sugar yield, covariates RHGS and EPDH which were strongly correlated with plant cane crop trial IPCA1 score (Table 7) could be the major environmental factors that caused the projection of plant cane crop trials C1W and C2B along both axes. Moreover, the positive and significant correlation of seasonal covariates EP and RHDH with plant cane crop trial IPCA2 scores of sugar yield indicated pan evaporation recorded during the growing season and relative humidity at harvest were the major environmental factors for separation of plant cane crop trial C1M (Figure not presented) as this trial was characterized with higher value of EP and RHDH. But we lacked concrete evidence for the negative and significant correlation of CS% with IPCA1 scores.

3.3.3. Environmental Factors Affecting the Pattern of Genotype x Location Interactions (GxL)

On the basis of the patterns of GxL interactions, AEP was positively correlated with location IPCA1 scores of cane yield and was the factor that caused for separation of location Belles. Percent of organic matter (OM %) and clay in soils

(CS %) influenced the patterns of GxL for cane yield as these covariates significantly correlated with location IPCA2 scores (Table 7) where locations Metahara and Finchaa were located (Figure 1(b)). The reason for substantial separation of location Tendaho along the first axis was not evident in terms of cane yield. For recoverable sucrose%, long year temperature regimes (AMXT, AMIT and AT) positively and significantly correlated location IPCA1 scores while long year maximum relative humidity (AMXRH) and altitude were negatively and significantly correlated with location IPCA scores of the this axis (Table 7). These covariates were the major environmental factors for separation of location Tendaho (Figure 2(b)) which was characterized by higher temperature regimes and lower altitude (Figure 4(d)). Moreover, the positive and significant correlation of long year maximum relative humidity (AMXRH) with IPCA1 scores indicated AMXRH could be the cause for small deviation of locations Wonji and Belles along the first axis while the positive correlation of percent of organic matter in soil (OM %) with location IPCA2 scores of recoverable sucrose% suggested OM% was the environmental factor behind the projection of location Metahara along the second axis.

Long year minimum relative humidity (AMIRH) and percent of organic matter in soil (OM %) were negatively and positively correlated respectively, with location IPCA1 scores for sugar yield. the strong correlation of these covariates with first axis was associated with the clear deviation of location Metahara along the first axis (Figure 3(b)). Furthermore, the significant and positive correlation of long year maximum relative humidity (AMXRH) with IPCA2 suggested AMXRH caused for the projection of locations Wonji and Finchaa which were characterized with higher value of long year maximum relative humidity. Such strong correlations of both long year seasonal covariates (maximum and minimum relative humidity) and site (clay and organic matter %) with IPCA scores suggest these covariates may be as influential on G × E interactions as everyone expected. Our results were contradicted with findings of Ramburan *et al.* [8] and Ramburan [21] where lack of frequent correlations between site covariates (clay) and trial IPCA scores of yield traits in sugarcane were observed.

3.3.4. Environmental Factors Affecting Genotype x First Ratoon Crop Trial Interactions (GxR)

As far as the ratoon crop trials is concerned, IPCA2 scores of ratoon crop trials for cane yield were negatively correlated with EPGS ($r = -0.95^{*}$) which was the cause for separation ratoon crop trial from location Wonji (R1W) along the second axis of the AMMI2 bi-plot for cane yield (Figure 4(c)) as this trial was characterized with lower EPGS in the PCA bi-plot (Figure 4(d)). Ratoon crop trial AMMI2 IPCA1 scores of recoverable sucrose% were strongly correlated with covariates MIT ($r = -0.99^{**}$), MT ($r = -0.98^{*}$) and TDH ($r = -0.94^{*}$). These covariates influenced the separation of ratoon crop trial at location Wonji (R1W) along the first axis of the AMMI2 bi-plot (figure not presented) as this trial was characterized by lower values of these covariates. Moreover, seasonal

covariates TDH (r = 0.979*), MIT (R = 0.95*), MT (r = 0.95*) and TGS (r = 0.99**) were strongly and positively correlated with ratoon trial IPCA1 scores of sugar yield while MRH was negatively and highly significantly correlated (r = −0.99**) with ratoon trial IPCA2 scores (figure not presented). These covariates were responsible for the projection of ratoon crop trial from Belles along both IPCA axes (figure not presented). Ratoon crop trials from locations Wonji and Finchaa showed less affinity to the covariates (**Figure 4(c)**) and loosely correlated with the IPCA scores (**Table 4**). Generally, the separation of C2T (plant cane crop trial at Tendaho Sugar Project) along the AMMI2 Biplot axes was not consistent with the effects of the environmental covariates that best characterized it in the PCA bi-plots (**Figures 4(a)-(c)**), which indicated the existence of extraneous factors involved which might be poor management practices. Of course, the trial was exposed to soil moisture stress at grand stage (data not shown) and was not justifiable through the analytical approach we followed in this study.

Generally, the analytical approach used was successful at identifying environmental variables that correlated with IPCA scores, as correlations of most covariates or variables were significant, especially for recoverable sucrose%. The influences of the environmental covariates on GEI patterns were effectively interpreted based on the environmental deviations along with AMMI2 IPCA axes in relation to the patterns the significant correlations with the environmental covariates studied. As suggested by Ramburan [21], significant correlations indicated any separation of the environments on the AMMI2 biplots is attributed to the relevant covariate, thereby highlighting the importance of that covariate to the GxE interactions. The patterns of GEIs and separations of the test environments were meaningfully displayed by the AMMI2 biplots. These patterns were similar to the environmental separations and mega environment classifications presented by GGE bi-plots in the GEI study reported by Mebrahtom [15] using the same dataset. With respect to the repeatability of the GEI, some discrepancy observed between the GGE and AMMI2 bi-plots. This could be attributed to the treatment of the G × E matrix prior to performing singular value decomposition as the GGE bi-plot technique utilizes environment centered data (matrix minus environment means) while AMMI uses the matrix of residuals (matrix minus genotype and environment means). Such differences were observed in similar studies reported by Ramburan [21] and De Vita *et al.* [23]. However, the lack of correlations observed between environmental AMMI2 IPCA scores and some specific covariates for cane and sugar yields were observed. This might arise from frequent fluctuations of seasonal averages. Moreover, other covariates which were not considered in this study were responsible for those associations. This demands to use a more comprehensive approach that considers other physiological indices and soil moisture stress indices.

4. Conclusions

AMMI2 analysis indicated that GEI and its components were all significant for

all yield traits included and the complexity nature of the interaction was in order of genotype x environment > genotype x plant cane crop trial > genotype x location interaction > genotype x First ratoon crop trial interactions. From variety recommendation point of view, genotypes PRS97 092, FG04 466, FG03 520, FG03 418 and DB66 113 produced higher sugar yield and were stable in wide range of environments (crop years and locations), and can be recommended for commercial purpose in sugarcane production areas of Ethiopia. Moreover, genotypes DB71 060 and FG04 187 were specifically adaptable to Finchaa and Belles agro climatic conditions and are recommended are specifically adaptable these production areas while genotype FG03 372 was specifically adaptable to location Wonji and is recommended for commercial purpose for Wonji agro climatic conditions.

The correlation analysis between the environmental factors and environmental AMMI2 IPCA scores successfully identified average pan evaporation (AEP), soil organic matter% (OM%) and clay% substantially influenced the genotype x location interaction (GxL) in cane yield while average minimum and maximum relative humidity (AMXT), soil organic matter% (OM%) and clay% influenced GxL patterns in sugar yield. all the average temperature and relative humidity regimes and site factors significantly influenced the GxL patterns in recoverable sucrose%. these covariates should be given priority when selecting contrasting sites for selection and evaluation. soil organic matter% (OM%), soil clay% (Cs%), relative humidity at harvest (RHDH) and growth stage (RHGS) and pan evaporation at establishment were the major factors for GxL interaction in cane yield while Maximum relative humidity recorded during the growing season (MXRH), all temperature regimes recorded during the entire growing season (MXT, MIT, MT) at different crop stages and pan evaporation at growth stage (EPGS) were the major factors that affect GEI in recoverable sucrose%. Moreover, the pattern of GEI in sugar yield was significantly affected by harvest age, percent of clay in soil (CS%), altitude, relative humidity at harvest (RHDH) and pan evaporation at establishment (EPE) these covariates should be recorded in genotype x environment interaction studies in sugarcane and should be considered during selection of environments for yield trials.

The possibility of finding significant correlation between environmental covariates and IPCA scores of AMMI2 decreased as the complexity of GEI interaction decreased and vise versa while the magnitude of the correlation kept stronger and stronger. However, the chance of identifying the appropriate causes of the interactions was greater when the GEI was partitioned in to its components. Compared to the cane and sugar yields, most of the temporal and spatial factors were more associated with the patterns of GEI and its components in recoverable sucrose%, highlighting the interactions were relatively less complex in recoverable sucrose%. It also suggests most of the variability observed in recoverable sucrose% was more of due to additive effects (due to genotype and environmental effects).

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Abbreviations

Additive Main Effects and Multiplicative Interaction (AMMI)

Genotype x environment interaction (GEI)

Multi-Environment Trials (MET)

Principal Component Analysis (PCA)