RESEARCH

Identifying Mega-Environments and Essential Test Locations for Pearl Millet Cultivar Selection in India

S. K. Gupta,* A. Rathore, O. P. Yadav, K. N. Rai, I. S. Khairwal, B. S. Rajpurohit, and R. R. Das

ABSTRACT

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is grown under a wide range of environmental conditions in India. The All India Coordinated Pearl Millet Improvement Project (AICPMIP) has the responsibility of testing and releasing pearl millet cultivars adapted to such conditions. As a part of this process, AICPMIP has divided the entire pearl millet growing regions into three different zones (A_1, A, and B) based on the rainfall pattern and local adaptation of the crop. This study was conducted to define the presently used test locations into possible mega-environments and to identify essential test locations for cost-effective evaluation of pearl millet cultivars. Grain yield data of different sets of 34 to 45 medium-maturity pearl millet hybrids tested at 29 to 34 locations during 2006 to 2008 were analyzed using genotype main effects and genotype × environment interaction biplot method. Two distinct pearl millet mega-environments with consistent grouping of locations across the years and corresponding to AICPMIP's designated A and B zones were identified. No such consistent grouping of locations corresponding to AICPMIP's designated A_1 zone was, however, observed. Based on the discriminating ability, uniqueness, and research resources, 13 locations were identified as essential test locations for evaluation across the two mega-environments. Testing at these locations appeared to provide good coverage of the whole pearl millet growing areas of India. Based on these findings, it is suggested to conduct initial yield trials at identified 13 locations across all the pearl millet growing zones represented by two mega-environments followed by testing of selected hybrids with specific adaptation in their respective adaptation zones.

S.K. Gupta, A. Rathore, K.N. Rai, I.S. Khairwal, and R.R. Das, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru-502324, Andhra Pradesh, India; O.P. Yadav, current address, Directorate of Maize Research (DMR), Pusa Campus, New Delhi-110012, India; B.S. Rajpurohit, All India Coordinated Pearl Millet Improvement Project (AICPMIP), Mandor, Jodhpur-342304, Rajasthan, India. Received 24 Jan. 2013 *Corresponding author (s.gupta@cgiar.org).

Abbreviations: AICPMIP, All India Coordinated Pearl Millet Improvement Project; ABD3, Aurangabad (Ajeet Seeds); ABD4, Aurangabad (Syngenta Seeds); ANR, Arya Nagar; BJR, Bijapur; BKR1, Bikaner; BUL, Buldana; BWL, Bawal; CBE, Coimbatore; DHL, Dhule; G, group; GGE, genotype main effects and genotype × environment interaction; GL, genotype × location; HOR, Hosur; HSR, Hisar; IHT, Initial Hybrid Trial; JDR, Jodhpur; JLG, Jalgaon; JMR, Jamnagar; JPR, Jaipur; KLI, Kalai; ME, mega-environment; LDA, Ludhiana; MDR, Mandor; NSD, Narsanda; RPR, Raipur; SKN, Sardar Krushi Nagar; SPR, Shikohpur.

Pearl millet is a hardy cereal grown globally on about 30 million ha, mostly in marginal environments of the arid and semiarid tropical regions of Asia and Africa, primarily for grain and fodder. Its grain serves as staple food in rural households. India is the largest producer of this crop, with 9.5 million t of grain from 9.3 million ha area (Yadav et al., 2011). The All India Coordinated Pearl Millet Improvement Project (AICPMIP) based at Mandor, Jodhpur (Rajasthan), is India's nodal center for coordinating national yield trials of hybrids and open-pollinated varieties with a network of about 30 to 35 test locations. Considering the rainfall pattern, local adaptation, and a wide range of environmental conditions under which pearl millet is grown, AICPMIP has divided

Published in Crop Sci. 53:2444–2453 (2013).
doi: 10.2135/cropsci2013.01.0053

the pearl millet growing area of India into three different zones (A_1, A, and B) for testing experimental hybrids bred by both public and private sectors. The A zone consists of northern and part of northwestern India, receiving >400 mm of annual rainfall. The A_1 zone consists of parts of northwestern India receiving <400 mm annual rainfall. The B zone consists of peninsular India, receiving >400 mm of annual rainfall. At present, about 75% of the pearl millet is grown in A and A_1 zones while B zone accounts for the remaining area. Experimental cultivars are tested vigorously for adaptation in these zones before their official release for cultivation.

A single cultivar of a crop can not be expected to perform well under all the environmental conditions (Rosielle and Hamblin, 1981; Ceccarelli, 1989) and a cultivar planted outside its zone of adaptation will suffer yield reduction due to significant genotype × location (GL) interactions. Therefore, planning of breeding and testing activities requires subdivision of the testing environments into relatively more homogeneous groups of locations, called mega-environments, where specific genotypes can be targeted for each of these groups of locations. Since pearl millet is primarily grown in marginal environments, which are stressed in a variety of ways, leading to large genotype × environment interactions, an understanding of the nature and relative contribution of genotype, locations, and GL interaction effects assumes greater importance in site selection, cultivar testing, and possible recommendation of genotypes for cultivation.

Latest statistical methods such as additive main effects and multiplicative interaction (Gauch, 1992) and genotype main effects and genotype × environment interaction (GGE) biplots (Yan and Kang, 2003; Yan and Tinker, 2006) are in use for genotype × environment data analysis. Recently, plant breeders and agronomists have found GGE biplots to be useful in mega-environment analysis (Yan and Rajcan, 2002; Casanoves et al., 2005; Samonte et al., 2005; Yan and Tinker, 2005; Dardanelli et al., 2006) and evaluation of test environments (Yan and Rajcan, 2002; Blanche and Myers, 2006; Thomason and Phillips, 2006). Although subdivision of crop growing region into several mega-environments increases the work for breeders to breed for each mega-environment separately, it also helps select genotypes for greater yield stability within relatively well-defined and homogeneous environments and hence increases the efficiency of breeding programs by targeting genotypes to appropriate production areas (Brown et al., 1983; Peterson and Pfeiffer, 1989; Abdalla et al., 1996). Furthermore, even if the breeding goal is wide adaptation, the best strategy would be to identify several mega-environments and use the most effective test locations in each to select for wide adaptation (Gauch and Zobel, 1997).

Although the present zoning of pearl millet growing region in India (A_1, A, and B zones) for breeding and testing purposes has been done considering agroclimatic factors of different regions, no systematic study has been conducted to characterize pearl millet mega-environments based on biological criteria. The objectives of this study, based on grain yield in AICPMIP's Initial Hybrid Trial (IHT) for 3 yr, were (i) to generate information on the magnitude and pattern of GL interactions across all pearl millet growing zones of India, (ii) to identify mega-environments and the extent to which the test locations in different zones represent their respective mega-environments, and (iii) to determine the minimum number of locations at which initial evaluations should be conducted to make hybrid testing cost effective.

MATERIALS AND METHODS

Test Materials and Locations

All India Coordinated Pearl Millet Improvement Project conducts medium-maturity IHT to test 35 to 45 new experimental hybrids (both bred by public and private sectors) every year at about 30 to 35 locations across three different zones of India (Fig. 1; Table 1). Grain yield data from this trial conducted in 2006, 2007, and 2008 were used for this study. The hybrids were evaluated using randomized complete block design with three replications at all locations following local crop management practices. The plot size was three rows of 5 m length spaced at 0.5 m. Upon maturity, all plants in a plot were harvested, panicles were sun dried for 10 to 15 d, and grain yield was determined on plot basis. Some of the locations were not common across the 3 yr. Of the 37 locations across 3 yr, 25 locations were used in all the 3 yr, eight locations were used in any 2 yr, and four locations were used in any 1 yr. Moreover, the hybrids evaluated each year were different because new hybrids are contributed by the participating centers each year. The hybrids for which data were available from all the locations in a particular year were considered for analysis. Therefore, data on 34 hybrids tested at 32 locations in 2006, 45 hybrids tested at 34 locations in 2007, and 34 hybrids tested at 29 locations in 2008 were used for this study.

Data Analysis

Analysis of variance using proc *glm* procedures of SAS software version 9.3 for Windows (SAS Institute, 2011) was performed yearwise to quantify the relative contribution of genotype main effects vs. GL interaction. Site regression analysis (Yan and Kang, 2003) was conducted yearwise to visualize the GL interaction patterns and the interrelationships among test locations. A two-dimensional GGE biplot (Yan and Tinker, 2006) that graphically depicts genotypic main effect and GL effect present in the multilocation trial data using environment centered data was constructed using GenStat 13th edition for Windows (VSN International, 2012). The SD-scaled GGE biplot was used for grouping of environments (Yan et. al., 2007) as the focus was to study similarities among test locations. The vectors representing locations in SD-scaled biplot should be of equal or similar length if the biplot adequately displays the patterns in the data. A shorter vector is an indication that the relevant location is not strongly associated with other locations (Yan and Fregeau-Reid, 2008). Unscaled GGE biplots were used to identify essential locations

Figure 1. Geographical positions of the pearl millet testing locations of Initial Hybrid Trial conducted by the All India Coordinated Pearl Millet Improvement Project in India under different crop zones (A_1, A, and B) in 2006, 2007, and 2008. See Table 1 for details on locations.

with high discriminating power. Locations in a particular year were partitioned into groups. Locations that came together in a cluster and closely related to one another in terms of genotype performance were pooled into smaller groups. In the process to identify essential test locations, if the test locations are highly similar, it may be possible to drop a few locations without much risk of losing a significant amount of information about the genotypes. Biplots were also constructed for the identified essential test locations. The rank correlations among the test locations of a particular mega-environment were used to find the degree of closeness among them (Malla et al., 2010).

RESULTS

Mega-Environment Analysis

Analysis of variance indicated that location main effect, genotype main effect, and GL were all highly significant in all the 3 yr (Table 2). The GL interaction accounted for 70.8 to 83.4% of the total variability due to genotype and GL interaction. Based on the GGE biplot analysis, 32 locations were partitioned into three mega-environments in 2006. Five of the nine locations representing A_1 zone (Jodhpur [JDR], Bawal [BWL], Mandor [MDR], Bikaner [BKR1], and Arya Nagar [ANR]) formed one mega-environment (ME1) while four of the A_1 zone, 10 of the 12 A zone, and three of the 12 B zone locations formed a second mega-environment (ME2). Nine of the B zone locations along with one A zone location formed the third mega-environment (ME3) (Table 3; Fig. 2a). In 2007, 34 locations were partitioned into two major mega-environments. All the nine A_1 zone locations, eight of the 12 A zone locations, and two of the 13 B zone locations clustered together to make one mega-environment (corresponding to ME2) while 11 B zone locations and four A zone locations made a separate cluster to represent another mega-environment

Table 1. Test locations for pearl millet evaluation in Initial Hybrid Trial (IHT-Medium) in India during 2006, 2007, and 2008.

Location	State	AICPMIP zone†	Location code	2006	2007	2008
Mandor	Rajasthan	A_1	MDR	√†	√	√
Jodhpur	Rajasthan	A_1	JDR	√	√	X‡
Bikaner	Rajasthan	A_1	BKR1	√	√	√
Jaipur	Rajasthan	A_1	JPR	√	√	√
Alwar	Rajasthan	A_1	ALW	√	√	X
Sardar Krushi Nagar	Gujarat	A_1	SKN	√	√	√
Hisar	Haryana	A_1	HSR	√	√	√
Bawal	Haryana	A_1	BWL	√	√	√
Arya Nagar	Haryana	A_1	ANR	√	√	X
Narsanda	Gujarat	A	NSD	√	√	X
Mahuwa	Gujarat	A	MHA	√	√	√
Anand	Gujarat	A	AND	√	√	√
Jamnagar	Gujarat	A	JMR	√	√	√
Ahmedabad	Gujarat	A	AHD	X	√	X
Vadodara	Gujarat	A	VDR	√	√	√
Kalai	Uttar Pradesh	A	KLI	√	√	√
Shikohpur	Uttar Pradesh	A	SPR	√	√	√
Raipur	Uttar Pradesh	A	RPR	√	√	√
Gwalior	Madhya Pradesh	A	GLR	√	√	√
Ludhiana	Punjab	A	LDA	√	√	√
New Delhi	New Delhi	A	NDL	√	√	√
Aurangabad (Ajeet Seeds)	Maharashtra	B	ABD4	√	√	√
Aurangabad (Syngenta Seeds)	Maharashtra	B	ABD3	√	√	√
Aurangabad (AICPMIP)	Maharashtra	B	ABD1	√	√	√
Dhule	Maharashtra	B	DHL	√	√	√
Mandwa	Maharashtra	B	MND	X	X	√
Jalna	Maharashtra	B	JLN2	√	√	X
Buldana	Maharashtra	B	BUL	√	√	√
Nagpur	Maharashtra	B	NPR	X	X	√
Ganewadi	Maharashtra	B	GNW	X	√	√
Jalgaon	Maharashtra	B	JLG	√	√	√
Bijapur	Karnataka	B	BJR	√	√	√
Palem	Andhra Pradesh	B	PLM	X	√	√
Anantapur	Andhra Pradesh	B	APR	√	√	√
Vavilala	Andhra Pradesh	B	VLL	√	X	X
Coimbatore	Tamil Nadu	B	CBE	√	√	√
Hosur	Tamil Nadu	B	HOR	√	√	X
Total number of locations				32	34	29

†AICPMIP, All India Coordinated Pearl Millet Improvement Project. These A_1 zone locations are also used to conduct A zone trials.

†√, trial planted and data available.

‡X, trial not planted.

(corresponding to ME3) (Table 3; Fig. 2b). The five A_1 zone locations (JDR, BWL, MDR, BKR1, and ANR) were in close proximity, as observed in 2006. Interestingly, all the B zone locations clustered together in ME3, except for Buldana (BUL) and Jalgaon (JLG), which were grouped in ME2. In 2008, 29 locations were partitioned into two major clusters. All the six A_1 zone locations and 4 of 10 A

Table 2. Mean squares for grain yield in All India Coordinated Pearl Millet Improvement Project's Initial Hybrid Trial of pearl millet (2006 to 2008).

Source	2006† df	2006† SS	2006† MS	2006† *F*-test	2007 df	2007 SS	2007 MS	2007 *F*-test	2008 df	2008 SS	2008 MS	2008 *F*-test
Genotype (G)	33	232,977,822	7,059,934	50.5**	44	265,909,380	6,043,395	36.0**	33	254,858,538	7,722,986	68.8**
Location (L)	31	2,603,803,615	83,993,665	600.8**	33	3,560,614,101	107,897,397	643.1**	28	1,372,914,480	49,032,660	437.3**
G × L	1,023	888,015,150	868,050	6.2**	1,452	1,334,177,460	918,855	5.4**	924	618,084,852	668,923	5.9**
Error	2,112	295,236,480	139,790		2,992	501,922,720.6	167,754.92		1,914	214,609,164	112,126	
G/(G + GL) (%)		20.78				16.62				29.19		
GL‡/(G + GL) (%)		79.22				83.38				70.81		

**Significant at the 0.01 probability level.

†SS, sum of squares; MS, mean squares.

‡GL, genotype × location.

Table 3. Distribution of locations (zone-wise) under different mega-environments in 2006, 2007, and 2008 based on All India Coordinated Pearl Millet Improvement Project's pearl millet Initial Hybrid Trial.†

Mega-environment (ME)	Zone	2006	2007	2008
ME1	A1	JDR, BWL, MDR, BKR1, and ANR	–	–
	A	–	–	–
	B	–	–	–
ME2	A1	SKN, JPR, HSR, and ALW	JDR, BKR1, MDR, SKN, ANR, HSR, BWL, ALW, and JPR	SKN, JPR, MDR, HSR, BWL, and BKR1
	A	RPR, JMR, SPR, NSD, GLR, LDA, VDR, KLI, AND, and MHA	RPR, VDR, KLI, JMR, AND, GLR, MHA, and NSD	NDL, AND, VDR, and SPR,
	B	BJR, DHL, and ABD4	BUL and JLG	PLM and BJR
ME3	A1	–	–	–
	A	NDL	NDL, AHD, SPR, and LDA	LDA, RPR, JMR, GLR, KLI, and MHA
	B	ABD1, BUL, LJN, APR, JLG, HOR, VLL, CBE, and ABD3	ABD1, DHL, PLM, HOR, ABD3, JLN2, GNW, ABD4, CBE, APR, and BJR	APR, ABD3, CBE, MND, BUL, ABD4, ABD1, JLG, DHL, GNW, and NPR

†ABD1, Aurangabad (AICPMIP); ABD3, Aurangabad (Syngenta Seeds); ABD4, Aurangabad (Ajeet Seeds); AHD, Ahmedabad ; ALW, Alwar; AND, Anand ; ANR, Arya Nagar; APR, Anantapur; BJR, Bijapur; BKR1, Bikaner; BUL, Buldana; BWL, Bawal ; CBE, Coimbatore ; DHL, Dhule; GLR, Gwalior; GNW, Ganewadi ; HOR, Hosur ; HSR, Hisar ; JDR, Jodhpur; JLG, Jalgaon; JLN2, Jalna; JMR, Jamnagar ; JPR, Jaipur; KLI, Kalai; LDA, Ludhiana; MDR, Mandor; MHA, Mahuwa; MND, Mandwa; NDL, New Delhi; NPR, Nagpur; NSD, Narsanda; PLM, Palem; RPR, Raipur; SKN, Sardar Krushi Nagar; SPR, Shikohpur; VDR, Vadodara; VLL, Vavilala.

zone and 2 of 14 B zone locations formed one mega-environment (corresponding to ME2) while 11 of the 14 B zone locations and six A zone locations clustered separately to form another mega-environment (corresponding to ME3) (Table 3; Fig. 2c).

Differentiation of All India Coordinated Pearl Millet Improvement Project's Zonal Locations

To better understand the relationship among the A_1 and A zone locations, SD-scaled biplots containing only A_1 and A zone locations were constructed (Supplemental Fig. S1; Table 4). Some locations such as BKR1 and Shikohpur (SPR) in 2006 (Supplemental Fig. S1a), SPR, BWL, and BKR1 in 2007 (Supplemental Fig. S1b), and BKR1 and New Delhi (NDL) in 2008 (Supplemental Fig. S1c) had shorter vectors than others, indicating that these locations were not strongly associated with other locations in the respective years, and information related to these locations was not well displayed in the biplot.

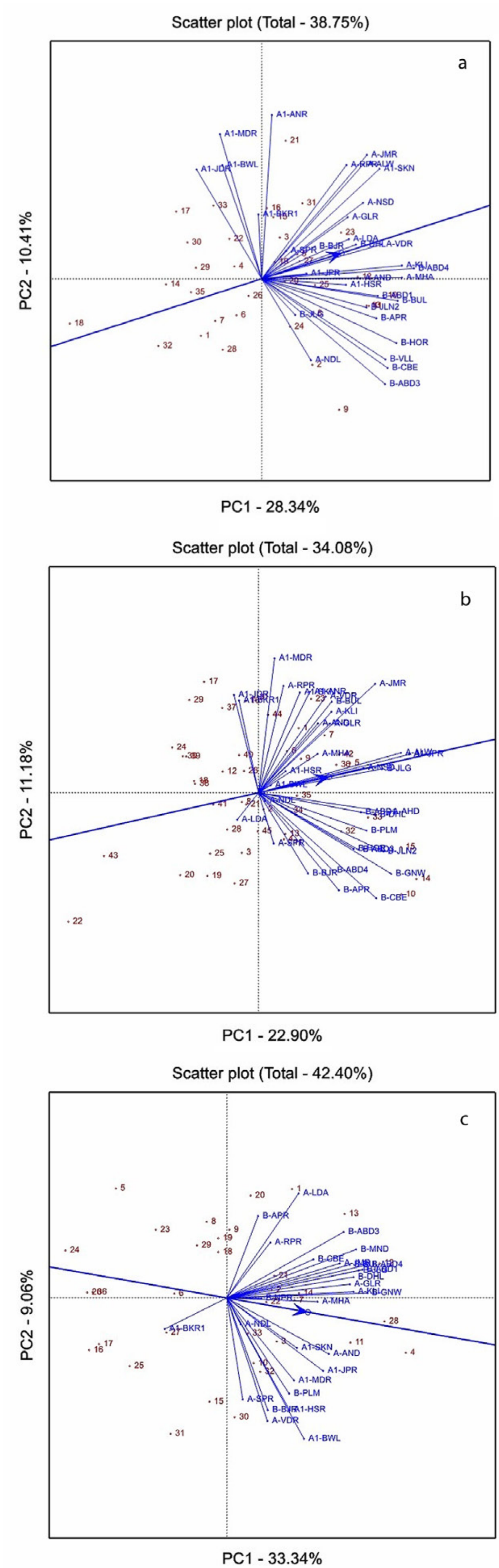
All the A_1 and A zone locations were partitioned into three groups in 2006, 2007, and 2008 (Supplemental Fig. S1a, S1b, and S1c; Table 4). Five A_1 zone locations (JDR, MDR, BWL, BKR1, and ANR) clustered together in 2006 and 2007, and two of them, BWL and MDR, clustered together again in 2008. Eight of the 11 A zone locations clustered together in 2006 as did 7 of the 12 A zone locations in 2007 and 6 of the 10 A zone locations in 2008.

All the B zone locations were partitioned into three groups in 2006 and two groups each in 2007 and 2008 (Supplemental Fig. S2; Table 4). In 2006, 10 of the 12 locations formed one group while two locations (Bijapur [BJR] and JLG) remained solitary. Bijapur and JLG had correlation coefficient of −0.58 ($p < .001$). Eight of the 13 B zone locations in 2007 and 9 of the 13 B zone locations in 2008 grouped together. All the three Aurangabad sites (Aurangabad [AICPMIP] [ABD1] and Aurangabad [Ajeet Seeds] [ABD3]) clustered together in all the 3 yr and had significant positive correlation with each other.

Identifying Essential Test Locations

The test locations within each group, identified above, were significantly positively correlated (numerical correlations not presented), which suggested that the same information about the performance of hybrids can be obtained from fewer test locations as from all the locations and hence number of test locations can be reduced, leading to reduction in the testing cost. Now, assuming that groups, as mentioned in Table 4, can be effectively represented by at least a single location, a set of essential locations were identified using multiple criteria. The main criterion was vector length in unscaled GGE biplots (not presented). Locations with longer vector length have greater discriminating power and hence would be preferred over other locations (Yan and Tinker, 2006). If a test location was not grouped with any other location or locations, then it was considered an essential test location because it presumably represented a unique environment and would likely provide unique information about genotype performance. The availability of facilities and human resources at the selected location to conduct precision experiments was used yet an additional criterion (Yan et al., 2010). Additionally, more essential test locations were selected from A_1 zone in comparison to other zones since A_1 zone, being more variable for climatic conditions, requires higher number of test locations for reliable assessment of the genotype performance.

In 2006, BWL was selected from the first A_1 and A group (G1) owing to the longest vector that depicts high discriminating power (based on unscaled GGE biplots). It is also AICPMIP's main test location in this group. In the second group (G2), Narsanda (NSD) had longest vector followed by Sardar Krushi Nagar (SKN) and Jamnagar



(JMR). Since NSD is not strong in terms of resources, SKN and JMR were selected for being premier research centers. In the third group (G3), Hisar (HSR) and Jaipur (JPR) were selected as both had long vectors and also both are relatively better resourced major AICPMIP centers. In the B zone groups, BJR was selected for being a unique location from G1. In G2, Hosur (HOR) had the longest vector followed by ABD3, BUL, and Coimbatore (CBE). Hosur and BUL are not strong in terms of resources and therefore ABD3 and CBE were selected for being major AICPMIP centers. Jalgaon was selected for being a unique location in G3.

In 2007, ANR from A_1 and A zone in G1 had longest vector followed by Kalai (KLI), Raipur (RPR), JDR, and MDR. However, ANR, KLI, and RPR are not strong centers in terms of resources, and therefore JDR and MDR from this group were identified. The well-resourced Central Arid Zone Research Institute, a premier institute for arid agriculture research in India, is located at JDR, and MDR is the well-resourced nodal AICPMIP center. In G2, NSD had longest vector followed by Ahmedabad (AHD), JPR, JMR, and SKN. However, JPR, JMR, and SKN were identified for being major AICPMIP centers. In G3, Ludhiana (LDA) was identified for having the longest vector. Amongst B zone groups, CBE had longest vector followed by ABD3 in G1 and hence both these locations were selected. In G2, HOR had longest vector followed by Dhule (DHL), but DHL was selected for being the major AICPMIP center.

In 2008, BWL had longest vector followed by HSR in G1 of A_1 and A zone and hence both were identified. Ludhiana (with longest vector) and JMR (with long vector) were selected in G2, and BKR1 in G3 was dropped due to short vector length. In the B zone, all the locations had short vectors in G1, so no location was identified. In the second group, Ganewadi (GNW) had longest vector followed by ABD3, Aurangabad (Syngenta Seeds) (ABD4), and JLG. However, ABD3, ABD4, and JLG were identified for being well-resourced centers.

Based on 3-yr analysis, 13 essential test locations were identified, which represented the minimum set of locations required for pearl millet cultivar testing in India.

Figure 2. Genotype plus genotype × location interaction biplots for all the locations for the (a) 2006, (b) 2007, and (c) 2008. See Fig. 1 for geographical positions of the locations. PC, principal component; ABD1, Aurangabad (AICPMIP); ABD3, Aurangabad (Syngenta Seeds); ABD4, Aurangabad (Ajeet Seeds); AHD, Ahmedabad ; ALW, Alwar; AND, Anand ; ANR, Arya Nagar; APR, Anantapur; BJR, Bijapur; BKR1, Bikaner; BUL, Buldana; BWL, Bawal ; CBE, Coimbatore ; DHL, Dhule; GLR, Gwalior; GNW, Ganewadi ; HOR, Hosur ; HSR, Hisar ; JDR, Jodhpur; JLG, Jalgaon; JLN2, Jalna; JMR, Jamnagar ; JPR, Jaipur; KLI, Kalai; LDA, Ludhiana; MDR, Mandor; MHA, Mahuwa; MND, Mandwa; NDL, New Delhi; NPR, Nagpur; NSD, Narsanda; PLM, Palem; RPR, Raipur; SKN, Sardar Krushi Nagar; SPR, Shikohpur; VDR, Vadodara; VLL, Vavilala.

Table 4. Subgrouping of locations (zonewise) and identification of essential test locations for pearl millet testing in 2006, 2007, and 2008.†

Year	Zone	Group no.	Location groups	Essential test location or locations	Essential test location‡
2006	A_1 and A	G1	JDR, MDR, BWL, BKR1, and ANR	BWL	MDR (1)
		G2	JMR, ALW, RPR, SKN, and NSD	JMR and SKN	JMR (3)
		G3	GLR, LDA, VDR, KLI, SPR, AND, MHA, JPR, HSR, and NDL	HSR and JPR	JDR (1)
	B	G1	BJR	BJR	BJR (1)
		G2	JLN2, DHL, ABD1, HOR, ABD4, APR, CBE, BUL, ABD3, and VLL	ABD3 and CBE	DHL (1)
		G3	JLG	JLG	CBE (2)
2007	A_1 and A	G1	SPR, NDL, JDR, BKR1, RPR, ANR, BWL, KLI, and MDR	MDR and JDR	JLG (2)
		G2	MHA, AND, GLR, VDR, JPR, JMR, ALW, SKN, AHD, and NSD	JMR,SKN, and JPR	
		G3	HSR and LDA	LDA	JPR (2)
	B	G1	ABD3, ABD4, BJR, APR, CBE, GNW, JLN2, and ABD1	CBE and ABD3	SKN (2)
		G2	JLG, HOR, PLM, DHL, and BUL	DHL	HSR (2)
2008	A_1 and A	G1	HSR, BWL, VDR, JPR, SKN, MDR, AND, SPR, and KLI	BWL and HSR	ABD (4)
		G2	GLR, MHA, JMR, NDL, RPR, and LDA	LDA and JMR	BWL (2)
		G3	BKR1	–	LDA (2)
	B	G1	NPR, APR, BJR, and PLM	–	
		G2	DHL, JLG, ABD1, MND, BUL, GNW, ABD4, ABD3, and CBE	ABD3, ABD4, and JLG	

†ABD1, Aurangabad (AICPMIP); ABD3, Aurangabad (Syngenta Seeds); ABD4, Aurangabad (Ajeet Seeds); AHD, Ahmedabad ; ALW, Alwar; AND, Anand ; ANR, Arya Nagar; APR, Anantapur; BJR, Bijapur; BKR1, Bikaner; BUL, Buldana; BWL, Bawal ; CBE, Coimbatore ; DHL, Dhule; GLR, Gwalior; GNW, Ganewadi ; HOR, Hosur ; HSR, Hisar ; JDR, Jodhpur; JLG, Jalgaon; JLN2, Jalna; JMR, Jamnagar ; JPR, Jaipur; KLI, Kalai; LDA, Ludhiana; MDR, Mandor; MHA, Mahuwa; MND, Mandwa; NDL, New Delhi; NPR, Nagpur; NSD, Narsanda; PLM, Palem; RPR, Raipur; SKN, Sardar Krushi Nagar; SPR, Shikohpur; VDR, Vadodara; VLL, Vavilala.

‡Number of years the location was selected as essential test location in parenthesis.

Validation of Essential Test Locations – Identifying High Yielding Hybrids

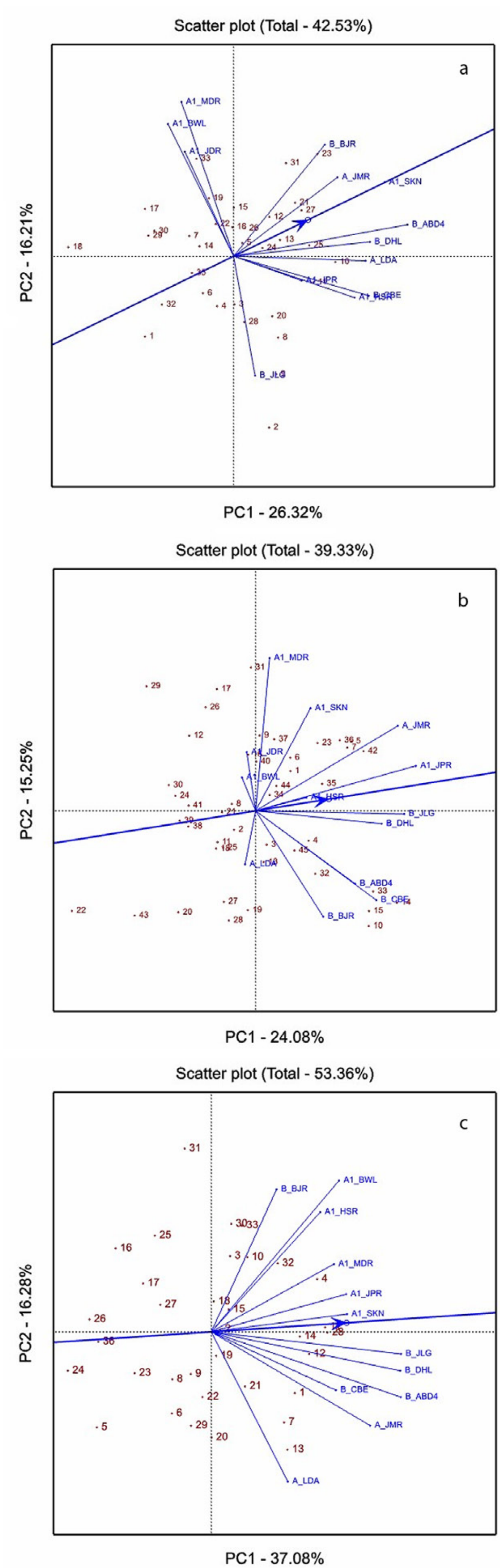
Biplots based on data from all the test locations (Fig. 2) were compared with the ones based on the essential test locations for 2006, 2007, and 2008 (Fig. 3). The high-yielding hybrids in an environment are visually identified as those that have projections onto the vector of the environment, which starts from the biplot origin and points to the marker of the environment. In 2006, the two highest-yielding hybrids (numbers 17 and 33) would be selected for A_1 zone, hybrids 23 and 31 would be selected for A zone, and hybrids 2 and 9 would be selected for B zone whether the selection was based on data from all the locations (Fig. 2a) or on the set of essential test locations (Fig. 3a). Also, hybrid 23, which was high yielding based on the data from all the locations (Fig. 2a), was found outstanding based on data from essential test locations (Fig. 3a).

For 2007, highest-yielding three hybrids (17, 31, and 37) would be selected for A_1 zone, five hybrids (5, 7, 23, 36, and 42) would be selected for A zone, and four hybrids (10, 14, 15, and 33) would be selected for B zone, whether the selection was based on data from all the locations (Fig. 2b) or on the set of essential test locations (Fig. 3b).

For 2008, three highest-yielding hybrids (4, 11, and 32) would be selected for the A_1 zone, whether based on data from all the locations (Fig. 2c) or on essential test locations (Fig. 3c). For B zone, hybrid 12 would be selected whether based on the data from all the locations or essential test locations. Also, hybrid 28, which was high-yielding based on data from all the locations (Fig. 2c), was found outstanding based on the data from essential test locations (Fig. 3c). Therefore, the 13 test locations appeared to represent well the whole of pearl millet growing regions, and testing at these locations appeared to be sufficient in any given year.

DISCUSSION

Grain yield data from different sets of medium-maturity pearl millet hybrids showed that GL interaction was much greater than genotype main effect in all the 3 yr, suggesting the possible existence of mega-environments in pearl millet growing regions of India. The grouping pattern of the locations showed that nine of the AICPMIP-designated 12 B zone locations in 2006 and 11 of the 13 B zone locations both in 2007 and 2008 clustered together, indicating that the B zone locations in peninsular India formed one separate mega-environment (ME3) in all the 3 yr, with a few exceptions of A_1 and A zone locations coming close to this mega-environment. Similarly, 8 to 10 of the 12 A zone locations in 2006 and 2007 and 6 of the 10 A zone locations in 2008 clustered together, indicating the existence of another mega-environment (ME2) in northern and northwestern India. Thus, the clustering pattern of locations across the 3 yr revealed the existence of two distinct mega-environments, each representing AICPMIP's A and B zone locations. This might be due to the contrasting differences that exist between these two zones for biophysical factors. The A zone comprises the northern states of Uttar Pradesh, Madhya Pradesh, Punjab, Delhi and parts of the northwestern states Rajasthan, Gujarat, and Haryana, which are at higher latitudes (21° N to 30° N), with Ustorthents, Ustochrepts, Chromusterts,



and Halaquepts soils, higher temperatures, and longer daylength, while the B zone comprises the central-southern Indian states of Maharashtra, Karnataka, Tamil Nadu, and Andhra Pradesh, which lie at lower latitudes (10° N to 21° N), with Paleustalfs, Rhodustalfs and Haplustalfs soils, mild temperature conditions, and shorter days. Moreover, most of the hybrids evaluated in medium-maturity IHT perform reasonably well in both A and B zones due to their natural adaptation and so were able to discriminate among the locations well for genotype rankings, leading to consistent and distinct clustering pattern across years. This consistency of grouping of locations in two mega-environments was observed in spite of different sets of genotypes tested in different years. Such consistency in partitioning of locations in mega-environments based on the testing of the same set of genotypes across years has also been observed in maize (*Zea mays* L.) (Annicchiarico, 1997), bread wheat (*Triticum aestivum* L.) (De Lacy et al., 1994), and durum wheat (*Triticum turgidum* L.) (Abdalla et al., 1996) and based on testing of different subsets of genotypes (Annicchiarico et al., 1995). Romagosa and Fox (1993) reported that multivariate analysis of new and known genotypes based on 1 yr of testing can provide reliable prediction of mega-environments for future years. However, if there is drastic change in plant genotype, reassessment of the mega-environments is needed (Braun et al., 1992). Therefore, occasional review and refinement of mega-environments should be an ongoing exercise (De Lacy et al., 1994).

In case of A_1 zone, five of the nine locations clustered together, apparently forming another mega-environment in 2006, while four locations from this zone grouped with A zone locations. All the nine A_1 zone locations in 2007 clustered with the major A zone locations, and five of these (JDR, BKR1, MDR, SKN, and ANR) were in close proximity. All the six A_1 zone locations clustered together with four A zone locations in 2008. Thus, A_1 zone locations had inconsistent clustering pattern across the 3 yr. The A_1 zone comprises of parts of northwestern states of Rajasthan, Gujarat, and Haryana, and early maturing hybrids are well adapted in this zone. This zone, receiving <400 mm of annual rainfall, is highly drought prone and has Camborthids, Calciorthids, Torripsamments, Natrargids, and Salorthids soils and high temperatures. This coupled with high coefficients of variation of annual rainfall in this zone, ranging from 40 to 80% over the years, leads to frequent crop failures (Yadav et al., 2011). The erratic rainfall pattern in A_1 zone within and between the

Figure 3. Genotype plus genotype × location interaction biplots including 13 essential locations for the (a) 2006, (b) 2007, and (c) 2008. See Fig. 1 for geographical positions of the locations. PC, principal component; ABD4, Aurangabad; BJR, Bijapur; BWL, Bawal; CBE, Coimbatore; DHL, Dhule; HSR, Hisar; JDR, Jodhpur; JLG, Jalgaon; JMR, Jamnagar; JPR, Jaipur; LDA, Ludhiana; MDR, Mandor; SKN, Sardar Krushi Nagar.

years significantly influences pearl millet yields, and hence inconsistent location-clustering patterns across years are not unexpected in this zone. Also, application of improved crop management practices, including fertilizer and irrigation, led to grain yield levels in the A_1 zone similar to those in A zone locations in these medium-maturity hybrid evaluation trials. Hence, it is not unexpected if the A_1 zone locations did not cluster together in a mega-environment separately from the A zone locations.

Thirteen essential test locations identified based on their discriminating ability, uniqueness of the environment, and available research facilities appeared to provide a good coverage of the three pearl millet growing zones of India. MDR, JDR, SKN, HSR, BWL, and JPR represented A_1 zone, JMR and LDA represented A zone, and BJR, DHL, CBE, JLG, and ABD4 represented B zone. The six locations representing A_1 zone can also be used for testing of medium-maturity hybrids adapted to A zone as these locations grouped with locations of the A zone mega- environment in all the 3 yr. Interestingly, AICPMIP is using all the nine A_1 zone locations mentioned in this study for evaluating medium-maturity hybrids for A zone. The hybrids selected for different zones remained largely the same whether based on all-location data or based on the data from the identified 13 essential test locations. This pattern was consistent in all the 3 yr. Therefore, the best strategy for the medium-maturity hybrids would be to conduct initial hybrid testing at all of these identified 13 essential test locations to identify those for further evaluation in advance trials in specific mega-environments.

As observed from Fig. 2a, 2b, and 2c, Supplemental Fig. S1a, S1b, and S1c, and Supplemental Fig. S2a, S2b, and S2c, hybrid 23 was identified in 2006 as the best hybrid based on all location analysis and in A_1 and B zone while it was amongst the top performers in A zone. Similarly, hybrid 28 was found to be one of the best performers based on all-location analysis and for A_1, A and B zones separately in 2008. The hybrid 23 in 2006 and hybrid 28 in 2008 were also found overall winners based on essential test locations. This showed the possibility of some hybrids, albeit in very low frequency, having wider adaptation across the mega-environments, thus highlighting the need of initial testing across mega-environments. Also, different sets of hybrids performed well in different zones in any particular year and so could be selected for reevaluations in advance trials in specific zone. For instance, hybrids 17 and 33 were found suitable for zone A_1, hybrids 31 and 23 for zone A, and hybrids 9 and 2 were found winners for zone B in 2006. These results are in agreement with past experience, as most of the hybrids bred and released till date have shown zone-specific adaptation and very few hybrids have shown wider adaptation across zones. Interestingly, AICPMIP evaluates new hybrids (both from public and private sector) in hybrid evaluation trial at national level across all the test locations shown in this study in all three zones followed by further evaluation in different zones as per their zone-specific performance. Following this methodology, AICPMIP released 28 hybrids during 2000 to 2009, of which three hybrids (a small but significant proportion) with wider adaptation were released for cultivation in all the three zones and the rest were released for specific zones (Khairwal et al., 2009). Therefore, hybrid development and release for adaptation to specific mega-environment should be, as currently followed by AICPMIP, the principal strategy, which also permits selection of hybrids with wider adaptation across the mega-environment.

Supplemental Information Available

Supplemental material is available at http://www.crops.org/publications/cs.

Supplemental Figure S1. Genotype plus genotype × location interaction biplots for A and A_1 zone locations for the (a) 2006, (b) 2007, and (c) 2008. See Fig. 1 for geographical positions of the locations. PC, principal component; AHD, Ahmedabad; ALW, Alwar; AND, Anand; ANR, Arya Nagar; BKR1, Bikaner; BWL, Bawal; GLR, Gwalior; HSR, Hisar; JDR, Jodhpur; JMR, Jamnagar; JPR, Jaipur; KLI, Kalai; LDA, Ludhiana; MDR, Mandor; MHA, Mahuwa; NDL, New Delhi; NSD, Narsanda; RPR, Raipur; SKN, Sardar Krushi Nagar; SPR, Shikohpur; VDR, Vadodara.

Supplemental Figure S2. Genotype plus genotype × location interaction biplots for B zone locations for the (a) 2006, (b) 2007, and (c) 2008. See Fig. 1 for geographical positions of the locations. PC, principal component; ABD1, Aurangabad (AICPMIP); ABD3, Aurangabad (Syngenta Seeds); ABD4, Aurangabad (Ajeet Seeds); APR, Anantapur; BJR, Bijapur; BUL, Buldana; CBE, Coimbatore; DHL, Dhule; GNW, Ganewadi; HOR, Hosur; JLG, Jalgaon; JLN2, Jalna; MND, Mandwa; NPR, Nagpur; PLM, Palem; VLL, Vavilala.

Acknowledgments

The support of the All India Coordinated Pearl Millet Improvement Project (AICPMIP) collaborators for sharing the data and that of Pearl Millet Hybrids Parents Research Consortium for partial funding is gratefully acknowledged. We appreciate Dr W. Yan for his valuable inputs during the course of this investigation.

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