Agroecological Patterns of Diversity in Pearl Millet [*Pennisetum glaucum* (L.) R. Br.] Germplasm from India

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India is the largest pearl millet growing country with diverse climate. Agroecological patterns of diversity for important agronomic traits was assessed in 5,197 pearl millet germplasm accessions originating in India and conserved at Rajendra S. Paroda Genebank at ICRISAT. Agroecological region 10, mostly covering Malwa and Bundelkhand regions, which accounted for maximum overall diversity with less representation in genebank (135 accessions), can be explored for additional diversity in the collection. Mean values and the frequency distribution suggest further exploration in agroecological region 3 for tall plant height, region 5 for short height, region 6 for high panicle exsertion and large seeds, region 8 for high number of productive tillers, region 10 for long panicles, region 11 for thick panicles, region 12 for late flowering and high tillering and region 14 for early flowering. Observed relationship between the climate of agroecological regions of India and the performance of pearl millet germplasm implies that the environmental factors such as rainfall, number of rainy days, temperature, soils and daily sunshine period are the important determinants of variation patterns.

Key Words: Agroecological region, Climatic zone, Geographical, Variation

Introduction

Pearl millet is one of the hardiest crops and its adaptation to a wide range of adverse environments makes it an important cereal in many countries of arid and semi-arid regions of Asia and Africa. India is the largest pearl millet growing country (10 million ha) contributing to 42 per cent production in the world (Bhatnagar, 2002). India, owing to its size, topography, and geographical position is characterized by extremely varied agroclimatic conditions on both seasonal and regional basis indicating wide genetic base in the crop germplasm. Information on climate at germplasm collection sites and the patterns of diversity distribution is very important for effective planning of future germplasm collection, conservation (Allard, 1970; Marshal and Brown, 1975) and its enhanced utilization in crop improvement programmes (Annicchiarico *et al.*, 1995; Hayward and Breese, 1993; Moreno-Gonzalez and Cubero, 1993). The availability of climatic and ecological databases and the new tools of Geographic Information System (GIS) in recent years have opened up new avenues for understanding and prediction of patterns of genetic diversity in natural populations. The Rajendra S. Paroda Genebank at ICRISAT holds the world's largest collection of 21,594 accessions of pearl millet germplasm, including 750 accessions of wild relatives from 50 countries. India is the major contributor with 6,647 accessions from a wide range of agroecological regions. In the present study, using the available passport information and characterization data of the accessions and the tools of GIS, we assessed the patterns of diversity for eight important agronomic characters of cultivated pearl millet germplasm collected in different agroecological regions of India.

Materials and Methods

The experimental material consists of 5,197 landraces of pearl millet germplasm originating from India and having information on geographic coordinates of collection site. The accessions were characterized in batches of 500-1000 at ICRISAT farm, Patancheru (17°25'N latitude, 78°00'E longitude and 545 m asl) in alfisols, during rainy season (June–November) from 1974 through 2006. Each accession was sown in two, 4 m long rows with spacing of 75 cm between rows and 10 cm between plants. Life saving irrigation was provided. Fertilizers were applied at the rate of 100 kg ha^{-1} N and 40 kg ha^{-1} P_2O_5. Rainy season at Patancheru is characterized by long (13.9 hrs. in June to 12.4 hrs. in November) and warm (minimum temperature: 21.8°C; maximum temperature: 30.9°C) days. The mean daily sunshine hours ranged from 4.1 in July to 8.3 in November with a mean of 6.0 during the crop growth. Data of eight important agronomic traits, days to 50% flowering, plant height, number of total and productive tillers, panicle exertion, length and thickness and 1000-seed weight were recorded using the Descriptors for Pearl millet (IBPGR and ICRISAT, 1993).

The delineation of the agroecological regions (20) of India developed by National Bureau of Soil Survey

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and Land Use Planning, Indian Council of Agricultural Research (ICAR), Nagpur, India was used in the present study (Sehgal *et al.*, 1992). Climatic zone is defined in terms of major climate variables that affect crop growth and is thus suitable for a certain range of crops and cultivars (FAO, 1983). Agroecological region is an area of the earth's surface characterized by distinct ecological responses to macroclimate as expressed by soils, vegetation, fauna and aquatic systems. Therefore, the agroecological region is the land unit carved out of climatic zones. The agroecological regions are more homogeneous both in terms of cropping patterns and climate and thus provide a better basis for studying crop responses to climatic variations (Carter and Konijn, 1988). Each climatic zone is divided in to 3-9 smaller agroecological regions depending on the rainfall, temperature, soils, vegetation, length of growing period, etc. Division of the Indian climatic zones has resulted in three agroecological regions (1, 2 and 3) in the arid zone, five regions (4, 5, 6, 7 and 8) in the semi-arid zone, nine regions (9, 10, 11, 12, 13, 14, 15, 16 and 17) in the sub-humid zone and three regions (18, 19 and 20) in the coastal zone (Fig. 1).

Geographic coordinates were retrieved to fill the gaps for accessions having location information using Microsoft Encarta^R, an electronic atlas (MS Encarta^R

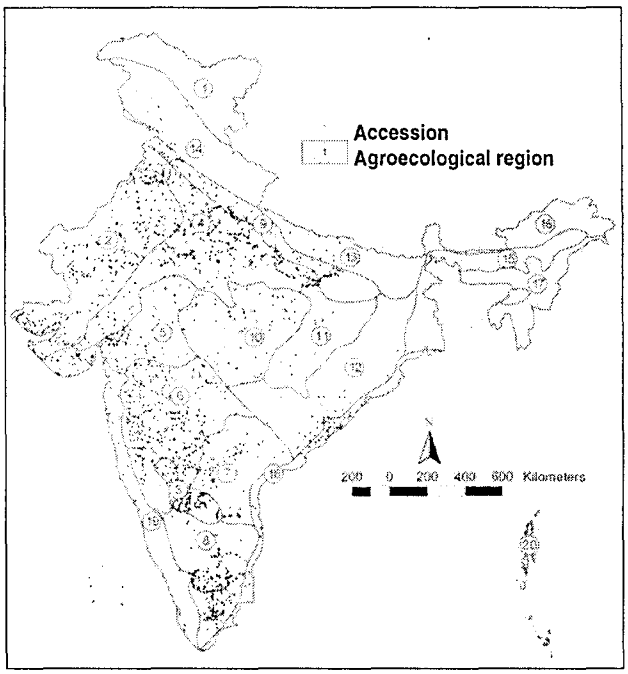

Fig. 1: Map of India, showing twenty agroecological regions (1-20) and the pearl millet germplasm collection sites (circles)

Interactive World Atlas, 2000) and the accuracy of coordinates was checked by mapping all accessions on to a political map of India. The information on mean minimum and maximum temperature and rainfall for each collection site was retrieved using DIVA-GIS software (Hijmans *et al.*, 2005a, b). ArcView^R-GIS was used to overlay the collection sites of all accessions along with characterization data on to the map of agroecological regions in India (Fig. 1). These two maps were spatially joined to separate the accessions from each agroecological region along with the characterization data. Data for selected traits of accessions from individual climatic zones and agroecological regions were analyzed for basic statistics using GENSTAT 6.1. Means, variances and diversity index (H') for all traits, climatic zones and agroecological regions within each zone were estimated and compared (Keuls, 1952; Newman, 1939; Levene, 1960; Shannon and Weaver, 1949). Frequency distribution of accessions within each extreme group/modality of different characters was estimated to identify the trait specific germplasm in each climatic zone and in different agroecological regions and discussed in light of available information on climatic factors at the collection sites.

Results and Discussion

Important characteristics of all climatic zones and agroecological regions of India along with the number of pearl millet germplasm accessions collected in each region are presented in Table 1. Semi-arid zone with 3,298 accessions (63.5%) followed by arid zone with 1,070 accessions (20.6%) are the major source of pearl millet germplasm. Among the agroecological regions, region 4 with 1,118 accessions (21.5%) and region 6 with 1,036 accessions (19.9%) are the major source of pearl millet germplasm. On the other hand, regions 11, 13, and 14 were under represented with <50 accessions and regions 1,15,16,17 and 20, which had very little pearl millet area are not represented in the collection (Fig. 1).

Newman-Keuls test of significance for mean values indicated significant differences between climatic zones and agroecological regions within each climatic zone (Table 2). Mean values indicated arid zone as the major source of early flowering and short statured pearl millet with significantly low mean values. Arid and semi-arid zones with highest means for 1000-seed weight differed significantly from sub-humid and coastal zones. Significant differences were found among the zones for total tiller number and pearl millet from coastal zone being the highest producer of total as well as productive tillers.

Table 1. Characteristics of climatic zones and agroecological regions of India and the number of accessions collected in each region

Climatic zone	Agro ecological region*	No. of accessions	Rainfall mm	Potential evapotrans-piration (mm)	Water deficit (mm)	Mean elevation (m)	Major soil type	Length of growing period (days)	Physiography
Arid	2	905	<300	1500-2000	1500-1800	190.9	Desert and saline	<90	Western plain and Kachchha peninsula
	3	165	400-500	1800-1900	1500-1800	536.6	Red and black	<90	Deccan plateau including Bellary, SW parts of Bijapur and Raichur of Karnataka and Ananthapur of A.P.
Semi-arid	4	1118	500-800	1400-1900	700-1000	227.2	Alluvium derived	90-150	Northern plains, central highlands including parts of Gujarat plains
	5	401	500-1000	1600-2000	800-1200	290.1	Medium and deep black	90-150	Central highlands (Malwa), Gujarat plains and Kathiawar Peninsula
	6	1036	600-1000	1600-1800	800-1000	503.1	Shallow and medium black	90-150	Deccan plateau including central and western parts of Maharashtra, northern parts of Karnataka and western parts of A.P.
	7	164	600-1000	1600-1700	700-800	283.5	Red and black	90-150	Deccan plateau (Telangana) and Eastern Ghats
	8	579	600-1000	1300-1600	400-700	465.8	Red loamy	90-150	Eastern ghats (Tamil Nadu uplands) and Deccan plateau (Karnataka)
Sub-humid	9	274	1000-1200	1400-1800	500-700	169.3	Alluvium derived	150-180	Northern plain (parts of Indogangetic plains and plains of W. Himalayas)
	10	135	1000-1500	1300-1500	500-700	440.3	Black and red	150-180 (210)	Central highlands (Malwa and Bundelkhand)
	11	45	1200-1600	1400-1500	500-700	419.2	Red and yellow	150-180	Eastern plateau (Chattisgarh region)
	12	85	1000-1600	1400-1700	500-700	330.9	Red and lateritic	150-180 (210)	Eastern plateau and Eastern Ghats
	13	18	1400-1600	1300-1500	400-500	78.2	Alluvium derived	180-210	Eastern plain
	14	24	1600-2000	800-1300	300-500	2738.0	Brown forest and podzolic	180-210	Western Himalayas
Coastal	18	178	00-1600	1200-1900	400-1000	31.2	Alluvium derived	90- (>210)	Eastern and coastal plain
	19	70	2000-3200	1400-1600	300-400	307.9	Red, lateritic and alluvium	>210	Western Ghats and coastal plain

* There were no collections from regions 1, 15, 16, 17 and 20 and hence not represented

As expected, accessions from coastal zone produced smallest seeds. Across the agroecological regions, Newman-Keuls test of significance for mean values indicated that region 2 and 5 for short height (<190 cm) and 1000-seed weight (=>7.7 g); region 3 for late flowering (77.4 days), tall (316.4 cm), and thick panicles (23.4 mm); region 6 for high panicle exsertion (8.6 cm), thickness (23.2 mm) and 1000-seed weight (8.09 g); region 7 for thick panicles (23.3 mm) and 1000-seed weight (7.8 g); region 8 for high total tiller number (4.4); region 10 for long panicles (24.8 cm); region 12 for late flowering (78.4 days), and high tillering (4.6); region 14 for early flowering (49.5 days), short height (185.4 cm) and long panicles (25.2 cm) and region 18 for high total (4.6) as well as productive (3.0) tiller number, as the most promising sources (Table 2).

Variances were heterogeneous (p=<0.01 to 0.001) for all traits in all climatic zones (Table 3). Similarly, variances were heterogeneous for all traits except total tillers among agroecological regions of arid zone; for all traits in regions of semi-arid zone; for days to 50% flowering, total tillers, productive tillers and 1000-seed weight in regions of sub-humid zone; and for days to 50% flowering, panicle exsertion and length in coastal zone (Table 3). Among agroecological regions, region 5 for panicle length; region 8 for plant height, total and

Table 2. Mean values for different characters in pearl millet germplasm from different climatic zones and agroecological regions within each zone of India, evaluated at ICRISAT, Patancheru, India

Climatic zone/ Agroecologocial region*	No. of accessions	Days to 50% flowering	Plant height (cm)	Total tillers (no.)	Productive tillers (no.)	Panicle exsertion (cm)	Panicle length (cm)	Panicle thickness (mm)	1000-seed weight (g)
Arid	1070	57.6c[1]	208.2b	3.4b	2.7b	6.8a	22.9a	21.4b	7.6a
2	905	54.0b	188.5b	3.4a	2.7a	6.7b	23.1a	21.1b	7.7a
3	165	77.4a	316.4a	3.3a	2.5a	7.9a	22.0b	23.4a	7.1b
Semi-arid	3298	60.2b	219.5a	3.2c	2.4c	6.7a	22.3a	22.0a	7.5a
4	1118	57.7b	221.4c	2.8b	2.3b	5.0c	24.5a	21.9b	7.6c
5	401	53.2c	183.1e	2.9b	2.3b	5.5c	23.3b	21.9b	7.9ba
6	1036	58.5b	201.9d	2.9b	2.1b	8.6a	19.1c	23.2a	8.0a
7	164	59.6c	242.0b	3.2b	2.3b	7.2b	22.9b	23.3a	7.8bc
8	579	73.1a	266.3a	4.4a	3.1a	7.5b	22.8b	19.8c	5.8d
Sub-humid	581	64.9a	226.2a	2.9d	2.3c	5.1b	23.0a	22.0a	7.2b
9	274	61.7b	230.6a	2.7b	2.3b	4.5bc	22.7ba	22.7a	7.6a
10	135	65.8b	233.8a	2.5b	2.1b	6.4ba	24.8a	22.2a	7.5a
11	45	66.3b	236.6a	2.5b	2.1b	5.3bc	23.1ba	22.2a	7.5a
12	85	78.4a	208.3b	4.6a	3.4a	4.4bc	20.7b	19.7b	4.9b
13	18	60.1b	216.1ba	2.4b	1.7b	3.3c	21.4b	22.8a	6.9a
14	24	49.5c	185.4c	2.3b	1.7b	8.1a	25.2a	21.5a	7.5a
Coastal	248	65.5a	222.0a	4.2a	2.9a	6.5a	22.3a	21.1b	6.1c
18	178	67.9a	218.1b	4.6a	3.0a	6.2b	21.7b	20.4b	5.8b
19	70	59.5b	231.9a	3.4b	2.6a	7.3a	23.6a	22.7a	7.0a

1=Means tested by Newman-Keuls test (same letters indicate non-significant and different letters indicate significant results at p=0.05)
* There were no collections from regions 1, 15, 16, 17 and 20 and hence not represented

Table 3. Variances for different characters in pearl millet germplasm from different climatic zones and agroecological regions of India, evaluated at ICRISAT, Patancheru, India

Climatic zone/ Agroecological region*	No. of accessions	Variance/ F value/ Pr>F	Days to 50% flowering	Plant height (cm)	Total tillers (no.)	Productive tillers (no.)	Panicle exertion (cm)	Panicle length (cm)	Panicle thickness (mm)	1000-seed weight (g)
Arid	1070	Variance	120.6	3540	3.1	1.5	15.4	25.1	12.9	1.7
2	905	Variance	42.2	1342	3.3	1.6	16.1	26	13.1	1.7
3	165	Variance	89.3	1740	1.8	1	10	19.3	7.1	1.2
		F value	32.08	5.01	3.42	4.57	5.46	2.38	17.65	2
		Pr>F[1]	<.001	0.025	0.065	0.033	0.020	0.012	<.001	0.016
Semi-arid	3298	Variance	181.6	3338	4	1.7	20	27.8	11	2.3
4	1118	Variance	60.2	1773	1.9	0.8	15.4	26.1	8.3	1.2
5	401	Variance	57.2	2112	2	1	14.5	32.5	12.3	1.2
6	1036	Variance	138.6	3123	1.6	0.8	22	18	7.5	1.8
7	164	Variance	103.1	1790	2.4	0.7	15.4	16.8	6.9	1.2
8	579	Variance	385.1	4240	12.6	5.4	16.2	18.9	14.7	2.7
		F value	244.61	42.94	24.21	53.18	7.09	14.69	24.71	39.84
		Pr>F	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Sub-humid	581	Variance	224.6	1580	3	1.4	18.1	23.2	11.4	2.3
9	274	Variance	68.8	1421	2.4	1.1	17.2	21.2	9.4	1.3
10	135	Variance	141	1363	0.9	0.8	17.3	30.2	11.2	1.1
11	45	Variance	79.3	1233	2.7	0.6	16.4	19.9	11.8	0.8
12	85	Variance	750.9	1961	6.1	2.7	18.7	13.4	14.3	3.4
13	18	Variance	71.3	1618	0.5	0.2	22.4	8.6	5.7	0.8
14	24	Variance	12.4	539	1.6	0.5	7.2	17.1	5.7	0.6
		F value	151.38	1.97	3.86	5.07	0.72	1.85	2.2	9.72
		Pr>F	<.001	0.081	0.002	0.001	0.607	0.101	0.528	<.001
Coastal	248	Variance	424.7	2250	9.4	2.7	14.3	18.8	11.4	3
18	178	Variance	469.7	2081	11.1	2.8	16.9	17.2	10.8	2.6
19	70	Variance	264.5	2579	4	2.4	7.2	20.6	9.5	2.8
		F value	7.16	0.76	0.68	0.03	4.62	0.78	0.39	0.14
		Pr>F	0.008	0.385	0.409	0.871	0.033	0.038	0.532	0.707
Over all zones		F value	45.15	26.55	4.28	1.98	6.63	4.5	3.16	9.01
		Pr>F	<.001	<.001	0.005	0.012	0.002	0.004	0.024	<.001

1=Variance homogeneity tested by Levene's test at p=0.05
* There were no collections from regions 1, 15, 16, 17 and 20 and hence not represented

productive tiller number and panicle thickness; region 12 for days to 50% flowering and 1000-seed weight and region 13 for panicle exertion showed the maximum variance.

The Shannon-Weaver diversity index (H') was calculated to assess the phenotypic diversity for all characters in different climatic zones and agroecological regions (Table 4). Across the climatic zones, highly diverse accessions were found in region 2 for days to 50% flowering; region 3 for productive tillers and 1000-seed weight; region 4 for panicle exsertion, panicle length, and thickness and 1000-seed weight; region 5 for panicle length; region 6 for total tiller number; region 8 for days to 50% flowering and 1000-seed weight; region 12 for panicle length and region 18 for plant height. Mean diversity index over all characters indicate accessions from region 4 (H'=0.68±0.019) and region 10 (H'=0.68±0.005) as highly diverse (Table 4). The high overall diversity in these two regions may be attributed to the alluvium derived soils of northern plains and central highlands and red and black soils of central highlands coupled with highly varied mean monthly minimum (27.5°C in June to 13.2°C in November) and maximum (39.4°C in June to 29.2°C in November) temperature in region 4 and mean monthly minimum (26°C in June to 13.9°C in November) and maximum (37.5°C in June to 28.8°C in November) temperature in region 10. Region 4 is well represented in the collection with 1,118 accessions. Region 10, which also accounted for maximum overall diversity with less representation in genebank (only 135 accessions), needs to be explored for additional diversity to augment world collection of pearl millet.

Frequency distribution for different trait extremes of all characters under study indicated arid zone as the promising source for early flowering, short height and large seeds; semi-arid zone for thick panicles, high panicle exsertion; sub-humid zone for tall and long panicles. Reflecting the higher length of growing period (90 to >210 days), high frequency of accessions from coastal zone was late flowering and produced high total as well as productive tillers (Table 5). Irrespective of climatic zone, frequency distribution indicated that agroecological region 3 was promising for tall plant height, region 5 for short plant height, region 6 for high panicle exsertion and large seeds; region 8 for more productive tillers; region 10 for long panicles; region 11 for thick panicles; region 12 for

Table 4. Shannon-Weaver diversity index (H') for different characters of pearl millet germplasm from different climatic zones and agroecological regions of India, evaluated at ICRISAT, Patancheru, India

Climatic zone/ Agroecological region*	Days to 50% flowering	Plant height (cm)	Total Tillers (no.)	Productive tillers (no.)	Panicle exsertion (cm)	Panicle length (cm)	Panicle thickness (mm)	1000-seed weight (g)	Mean
Arid	0.62	0.66	0.64	0.67	0.66	0.67	0.69	0.64	0.66 ± 0.008
2	0.69	0.7	0.65	0.68	0.66	0.64	0.68	0.63	0.67 ± 0.009
3	0.59	0.69	0.64	0.71	0.61	0.63	0.69	0.71	0.66 ± 0.017
Regional mean	0.64±0.050	0.70±0.005	0.65±0.005	0.70±0.015	0.64±0.025	0.64±0.005	0.69±0.005	0.67±0.040	0.66 ± 0.005
Semi-arid	0.59	0.68	0.51	0.57	0.69	0.7	0.67	0.69	0.64 ± 0.025
4	0.68	0.67	0.56	0.66	0.72	0.7	0.73	0.71	0.68 ± 0.019
5	0.55	0.68	0.63	0.68	0.67	0.7	0.69	0.69	0.66 ± 0.017
6	0.65	0.64	0.69	0.68	0.66	0.66	0.7	0.69	0.67 ± 0.007
7	0.67	0.67	0.57	0.65	0.62	0.62	0.71	0.69	0.65 ± 0.016
8	0.69	0.68	0.42	0.43	0.67	0.69	0.69	0.71	0.62 ± 0.043
Regional mean	0.65±0.025	0.67±0.007	0.57±0.049	0.62±0.048	0.67±0.016	0.67±0.015	0.70±0.007	0.70±0.005	0.66 ± 0.010
Sub-humid	0.65	0.69	0.56	0.62	0.68	0.69	0.69	0.67	0.66 ± 0.016
9	0.68	0.66	0.55	0.60	0.71	0.67	0.69	0.69	0.66 ± 0.019
10	0.67	0.7	0.66	0.69	0.68	0.67	0.66	0.69	0.68 ± 0.005
11	0.52	0.67	0.36	0.68	0.69	0.67	0.61	0.65	0.61 ± 0.040
12	0.66	0.69	0.62	0.65	0.64	0.7	0.68	0.67	0.66 ± 0.009
13	0.56	0.54	0.62	0.63	0.64	0.64	0.58	0.68	0.61 ± 0.016
14	0.59	0.69	0.62	0.53	0.63	0.62	0.71	0.62	0.63 ± 0.020
Regional mean	0.61±0.027	0.66±0.024	0.57±0.045	0.63±0.024	0.67±0.013	0.66±0.011	0.66±0.020	0.67±0.011	0.64 ± 0.012
Coastal	0.5	0.68	0.5	0.56	0.61	0.66	0.7	0.68	0.61 + 0.029
18	0.55	0.71	0.45	0.54	0.64	0.66	0.71	0.69	0.62 ± 0.034
19	0.39	0.63	0.62	0.61	0.65	0.68	0.66	0.68	0.62 ± 0.033
Regional mean	0.47±0.080	0.67±0.040	0.54±0.085	0.58±0.035	0.65±0.005	0.67±0.010	0.69±0.025	0.69±0.005	0.62 ± 0.000
Regional grand mean	0.61±0.022	0.67±0.011	0.58±0.025	0.63±0.020	0.66±0.008	0.66±0.007	0.68+0.010	0.68±0.007	0.65 ± 0.033

* There were no collections from regions 1, 15, 16, 17 and 20 and hence not represented

Table 5. Frequency distribution (%) for different trait extremes of each character in pearl millet germplasm from different climatic zones and agroecological regions of India, evaluated at ICRISAT, Patancheru, India

Climatic zone/ Agroecological region*	Days to 50% flowering		Plant height (cm)		Total tillers (no.)		Productive tillers (no.)		Panicle exertion (cm		Panicle length (cm)		Panicle thickness (mm)		1000-seed weight (g)	
	Early (<45)	Late (>80)	Short (<125)	Tall (>250)	Low (<2)	High (>7)	Low (<2)	High (>7)	Poor (< 0)	Good (>12)	Small (<15)	Long (>30)	Thin (<15)	Thick (>30)	Small (<5)	Large (>10)
Arid	5.05	7.01	4.67	17.01	22.06	4.21	37.57	0.56	5.23	5.14	4.21	5.51	2.43	0.65	1.87	2.80
2	5.97	0.22	5.52	3.20	23.20	4.64	37.46	0.66	5.75	5.08	3.76	6.30	2.76	0.66	1.66	3.20
3	0.00	44.24	0.00	92.73	15.76	1.82	38.18	0.00	2.42	5.45	6.67	1.21	0.61	0.61	3.03	0.61
Semi-arid	3.70	8.82	4.40	24.08	25.17	2.97	46.88	1.30	7.82	8.46	9.25	4.34	2.79	0.70	7.34	1.97
4	1.79	0.27	4.11	24.51	25.49	1.25	42.58	0.09	12.61	2.06	2.95	7.78	0.72	0.27	0.81	0.89
5	2.99	0.75	15.96	5.99	31.92	0.75	49.38	0.25	7.48	2.00	5.74	7.23	0.75	1.50	0.25	2.99
6	7.72	5.69	3.28	14.09	29.05	0.58	54.63	0.00	4.73	18.63	22.39	0.48	0.10	0.87	2.03	3.38
7	3.05	4.88	0.00	35.98	16.46	3.05	44.51	0.00	4.88	3.66	2.44	1.83	1.22	0.61	2.44	3.05
8	0.86	37.65	0.17	50.26	15.37	12.09	40.24	7.08	5.18	8.46	2.25	3.28	13.47	0.69	35.75	0.52
Sub-humid	2.75	10.15	0.86	31.33	35.80	3.27	51.46	0.86	12.22	2.41	2.41	5.68	2.75	0.52	8.95	1.03
9	0.73	0.36	0.73	36.13	37.59	2.55	55.47	0.36	13.87	2.19	1.09	3.65	1.46	0.36	0.36	1.09
10	2.96	13.33	0.74	36.30	41.48	0.00	55.56	0.00	10.37	3.70	4.44	13.33	0.00	0.74	1.48	0.74
11	2.22	2.22	0.00	33.33	46.67	2.22	53.33	0.00	13.33	2.22	0.00	6.67	0.00	2.22	0.00	0.00
12	7.06	45.88	1.18	16.47	9.41	12.94	18.82	4.71	10.59	1.18	5.88	1.18	14.12	0.00	57.65	2.35
13	0.00	0.00	5.56	27.78	33.33	0.00	72.22	0.00	22.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	12.50	0.00	0.00	0.00	58.33	0.00	79.17	0.00	0.00	4.17	0.00	4.17	0.00	0.00	0.00	0.00
Coastal	3.63	22.98	1.61	18.95	12.50	7.66	29.84	2.02	5.24	2.82	5.24	1.61	6.05	0.00	29.03	0.81
18	4.49	25.28	2.25	19.10	8.43	8.99	26.40	1.69	6.74	2.81	5.62	1.69	7.87	0.00	35.39	0.00
19	1.43	17.14	0.00	18.57	22.86	4.29	38.57	2.86	1.43	2.86	4.29	1.43	1.43	0.00	12.86	2.86

* There were no collections from regions 1, 15, 16, 17 and 20 and hence not represented

late flowering, high tillering, and region 14 for early flowering (Table 5).

Frequency distribution and mean values for different agroecological regions indicated unequal diversity distribution of pearl millet for different traits. Region 14, located at higher elevations (2738 m asl) followed by region 2 with typical arid climate are the most promising sources for early flowering. Being a short day crop, pearl millet adapted to higher sunshine (8.6 hours/day) and lowest minimum (16.1°C) and maximum (28.3°C) temperature in region 14 flowered early when evaluated under relatively low sunshine (6.0 hours/day) at Patancheru conditions showing their sensitivity to photoperiod (Fig. 2) (Arnold, 1959; Ferere, 1984; Bidinger and Rai, 1989). None of the accessions from region 14 flowered late. Region 2 with typical hot arid climate with lowest mean annual rainfall of <300 mm and lowest mean number of rainy days (3 days), highest mean minimum and maximum temperature during June (27.4°C and 39.0°C) and July (26.4°C and 35.0°C) at collection sites and desert sandy soils, which holds low water and causes mild water stress conditions had lowest length of growing period (Fig. 2, Table 1) (Sehgal *et al.*, 1992). The pearl millet adapted to such conditions is expected to flower early and grows to a short height. Angus and Monur (1977) reported that mild water stress hastened anthesis in wheat, while severe stress delayed anthesis. Mahalakshmi *et al.* (1987) reported reduced plant height and increased tiller number due to water stress during early stages and stem elongation period. Interestingly, all early flowering, short height and high productive tillering accessions of arid zone are from region 2, where mild moisture stress is common (Fig. 2).

On the other hand, agroecological region 12 followed by region 3, receiving erratic rainfall and having red, lateritic soils, which cause severe water stress conditions in early stages of crop growth, are the good source of late flowering accessions, which produced more tillers having small and thin panicles (Angus and Monur, 1977; Lahiri and Kumar, 1966; Mahalakshmi and Bidinger, 1985). Increased tillering results in the reduced panicle and seed size primarily due to the reduced availability of current photosynthates for seed filling (Mahalakshmi and Subramanian, 1985). Deviation from the expected length of growing period in region 3, the smallest region with very different climate from that of other regions may be attributed mainly to the erratic rainfall (5 days per month), which is more common in Southern India than in Northern India (Fig. 2) (Harinarayana, 1987; Mahalakshmi and Bidinger, 1986). Furthermore, continuous rainy days and amount of rainfall plays important role in deciding the length of growing period in any region (Gadgil *et al.*,

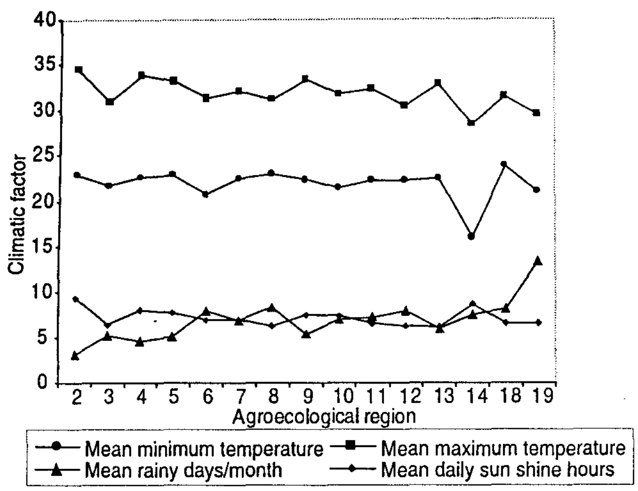

Fig. 2: Monthly mean minimum and maximum temperature, rainy days per month and daily sunshine hours at the collection sites of pearl millet germplasm accessions during crop season (June to November)

1988; World Water and Climate Atlas October, 2000). Sensitivity of the accessions, particularly to the photoperiod also contributed to late flowering in pearl millet from these two regions. When compared to the accessions from all other types of soils, red and black soils and mixture of these two soils resulted in high frequency (56%) of tall accessions (Table 5). Pearl millet adapted to such soil conditions in region 3, where red and black soils are predominant, resulted in high frequency (92.7%) of tall accessions (>250 cm).

Probably high total rainfall, high mean rainy days per month (about 8 days/month), coastal climate and red and lateritic soils in region 12 and red loamy soils in region 8 have resulted in high tillering (Fig. 2) (Fussel *et al.*, 1980; Harinarayana, 1987). High rainfall and fertile soils of the region 10 and 11 resulted in high frequency of accessions with long and thick panicles, respectively. Probably due to salinity in some areas and intermittent dry spells causing stress conditions during stem elongation, the highest frequency (15.96%) of short stature accessions was in region 5 (Mahalakshmi and Bidinger, 1985; Mahalakshmi *et al.*, 1987; Sehgal *et al.*, 1992). Region 6 with black soils and optimum temperature at panicle development stage resulted in more accessions with highly exserted panicles with large seeds (Fussel *et al.*, 1980; Ong and Monteith, 1985; Sehgal *et al.*, 1992).

In general, the results indicated that the pearl millet from southern and eastern parts of India was good source for late flowering, tall, high tillering, and small panicles with smaller seeds; whereas the pearl millet accessions from northern and western parts of India was good source for early flowering, short height and large seeds. Results illustrated a closer relation between the climate of agroecological regions and the performance of pearl millet germplasm for different characters, implying that the environmental factors such as rainfall, temperature, daily sunshine hours and soils are the important determinants of variation patterns of pearl millet in different climatic zones and agroecological regions suggesting the need to record sufficient data on agrometeorological variables, in particular, rainfall, temperature, daily sunshine hours and soil type at collection sites (Reddy *et al.*, 2004). Studies in different crops have shown that a careful investigation of climatic variables can lead to the identification of germplasm with useful and predictable attributes (Rick, 1973; Klebesadel and Helm, 1986). Therefore, the assessment of diversity patterns in relation to the crop ecology of more homogeneous and smaller agroecological regions revealed patterns of diversity in a better way (Carter and Konijn, 1988; Sehgal *et al.*, 1992). Natural selection pressure for adaptation to different climatic and agroecological conditions coupled with farmer's selection for cultivation of a specific type of material in adverse conditions in some areas might have accounted for the observed patterns of diversity.

Since, the pattern of diversity for each character varied in different climatic zones and agroecological regions within each climatic zone, collection missions could be effectively planned for trait-specific pearl millet germplasm. Using the diversity patterns in different agroecological regions, cost effective collection missions could be prioritized to explore high diversity regions, under-collected and threatened areas for materials of interest. Though the evaluation data used in the present study are preliminary in nature, and recorded over years, these data reflect the differences in the genetic makeup of the accessions in terms of clear patterns of diversity. Further, such studies help in identifying suitable sites for regeneration of trait-specific germplasm sets and introduction of appropriate pearl millet into different regions and emphasize similar studies on germplasm collections from different countries.

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