Genet Resour Crop Evol (2008) 55:379–387
DOI 10.1007/s10722-007-9245-2

RESEARCH ARTICLE

Diversity in Tanzanian pigeonpea [*Cajanus cajan* (L.) Millsp.] landraces and their response to environments

E. O. Manyasa · S. N. Silim · S. M. Githiri · J. L. Christiansen

Received: 6 December 2006 / Accepted: 23 April 2007 / Published online: 22 June 2007

Abstract A total of 123 pigeonpea landraces collected from farmers' fields in four pigeonpea growing regions of Tanzania were characterized and evaluated for 16 qualitative and 14 quantitative descriptors, and their response across three pigeonpea growing environments in Tanzania and Kenya determined. Polymorphism in the qualitative traits was relatively low among accessions and across collection regions. Collections from the northern highlands exhibited lower diversity in qualitative descriptors, especially physical grain characters, relative to the other three regions, an indication of farmer selection in response to market preferences. There were significant differences in agronomic traits among accessions and in genotype-by-environment interaction (GEI). High broad-sense heritability was recorded for days to flower, days to maturity, plant height, raceme number and 100 seed mass. Principal component analysis and clustering separated variability among the accessions according to days to flower, days to maturity, plant height, number of primary and secondary branches, and number of racemes per plant. There was close clustering within and between materials from the coastal zone, eastern plains and southern plains with the northern accessions distinctly separated and with wide dispersion within them. Overall, two diversity clusters were evident with coastal, eastern and southern landraces in one diversity cluster and northern highlands landraces in another cluster. This diversity grouping established potential heterotic groups which may be used in crosses to generate new cultivars adapted to different pigeonpea growing environments with consumer acceptability. The grouping may also form a basis of forming a core collection of this germplasm representing the variability available.

Keywords Agro-ecologies · Agro-morphological · *Cajanus cajan* · Multivariate analysis · Pigeonpea · Tanzania

E. O. Manyasa (✉) · S. N. Silim
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), P.O. Box 39063, Nairobi 00623, Kenya
e-mail: e.manyasa@cgiar.org

S. M. Githiri
Department of Plant Science and Crop Protection, University of Nairobi, P.O. Box 29053, Nairobi, Kenya

J. L. Christiansen
Department of Agricultural Sciences, The Royal Veterinary and Agricultural University (KVL), 40 Thorvaldsensvej, 1871 Frederiksberg C, Copenhagen, Denmark

Introduction

Pigeonpea (*Cajanus cajan*), a legume crop of the tropics and subtropics, is the fifth most important pulse crop in the world (Whiteman et al. 1985). In Tanzania, pigeonpea is the third most important legume crop and is grown on more than 55,000 ha with an average production of 38,000 t (Shiferaw et al. 2005). Although the northern highlands where the crop is getting commercialized is the major production region, the crop is also extensively cultivated along the coast, Morogoro and southern regions of the country (Shiferaw et al. 2005). Yields on farmers' fields are low (400–700 kg ha^{-1}) due to poor cultivars, poor crop husbandry and high losses resulting from insect pests and diseases (Shiferaw et al. 2005). Most cultivars grown in Tanzania are medium and long duration landraces. However, in the northern region, long duration, improved cultivars developed by ICRISAT's eastern Africa regional program using local germplasm are now being adopted (Silim et al. 2005).

No systematic collection and characterization of pigeonpea has been carried in Tanzania. As better yielding improved cultivars are adopted by farmers, there is high likelihood of diversity loss in this crop. This led ICRISAT researchers and national partners in Tanzania to conduct a comprehensive collection mission in 2001 in four major pigeonpea growing areas where a total 123 accessions were obtained. The knowledge of the amount, extent and distribution of genetic variations in germplasm is the key to its improvement and development of effective conservation strategies (Hodgkin 1997). The study of agro-morphological traits together with sound multivariate statistical procedures that characterize genetic divergence using the criterion of similarity or dissimilarity based on aggregate effect is the classic way of assessing genetic diversity (Mead et al. 2002) and can be used for grouping of the germplasm without prior knowledge of area of origin or germplasm groupings (Ogunbodede 1997).

This research aimed at determining the extent of genetic divergence in pigeonpea landraces collected from four major pigeonpea production regions of Tanzania based on agro-morphological descriptors and their response in different pigeonpea production environments to provide information that would enable germplasm management and use in breeding programs.

Materials and methods

Germplasm, trial site description, experimental design and crop management

The 123 pigeonpea landrace accessions collected from four main pigeonpea growing regions in Tanzania were used in this study. The accessions consisted of 23 from the coastal zone, 34 from the eastern plain, 36 from the southern plains and 30 from the northern highlands. The 123 accessions plus 21 medium and long duration cultivar checks were grown and evaluated for 30 agro-morphological traits at two sites in Kenya: Kampi ya Mawe (1250 m altitude, 1^0 57′ S, mean temp. 23°C and mean annual rainfall 500–600 mm) and Kabete (1960 m altitude, 1°14′ S and mean temp. 18°C and mean annual rainfall 1046 mm) and at one site in Tanzania: Ilonga (506 m altitude, 6°46′ S and mean temp. 22°C and mean annual rainfall 1046 mm). The check cultivars were those with known adaptation and released or to be released to farmers in Tanzania, Kenya, Uganda, Malawi and Mozambique. However, the checks were only used in PCA biplots and cluster analysis to determine their separation relative to the 123 accessions. The cropping seasons for the trials were in 2002/03 in Tanzania and 2004/05 in Kenya. At all the sites, the accessions were planted in a 12×12 square Lattice Design with 3 replications. Plots were 4 m length and inter-row and intra-row spacings were 1.5 m and 0.5 m, respectively.

Agro-morphological traits, data collection and analysis

IBPGR/ICRISAT Descriptors (1993) was used for data collection. At each site in Kenya, data were collected on 16 qualitative and 14 quantitative traits, however, due to manpower limitations data were taken on only five qualitative and seven quantitative traits at Ilonga. Qualitative data were recorded on individual plants within the plot for each replication except for seed traits which were recorded on a sample from a whole plot. Data on number of primary branches, number of secondary branches, number of racemes, pods per plant, and pod bearing length were taken on five randomly selected plants in each plot. Pod length, pod width and number of seeds per pod were recorded on ten pods selected randomly from five plants in the plot whereas pods per raceme and raceme length were recorded on ten racemes randomly selected from five plants in the plot. Days to flower and days to maturity, and pod and grain yields were taken on a plot basis. All data analyses were done using Genstat 8.0 statistical software. Shannon–Weaver diversity indices as described by Jain et al. (1975) were calculated for qualitative traits based on phenotypic frequencies of each trait category to estimate phenotypic diversity among and within the accessions and within collection regions. Frequencies of occurrence of each category in each trait were also calculated.

Analyses of variance were done using unbalanced design instead of the square lattice used in planting due to missing entries (failure to germinate). Broad sense heritability estimates using combined site variance components were made following Haryanto (2002) as the ratio between genetic variance (V_G) and phenotypic variance (V_P). Quantitative traits were subjected to Principal Component analysis (PCA) to determine patterns of variation and major traits contributing to the delineation. The correlation matrix was standardized to minimize effect of scale on variability weighting (Fundora Mayor et al. 2004). Only principal components (PCs) with Eigen-values above 1 were considered in determining the agro-morphological variability in the accessions (Kaiser 1960). The first two PCs were plotted to enhance the dispersion of the 123 accessions. A cluster analysis was carried out based on Euclidean distance matrix in a hierarchical way (Fundora Mayor et al. 2004) using average linkage analysis.

Results and discussion

Qualitative descriptors

Base flower colour, flowering pattern, pod colour, pod form, streak pattern, second seed colour, seed colour pattern and seed shape accounted for the polymorphism in the 123 accessions (Table 1). The predominant semi-spreading growth habit observed (93%) is a reflection of the cropping systems in the pigeonpea growing areas of eastern Africa where intercropping with cereals and other legumes is widely practiced and these pigeonpea types are preferred (Silim et al. 2005) due to their high branching plasticity (Baldev 1988). Most of the accessions in this study had indeterminate flowering pattern (59%), yellow flower colour (73%), red

Table 1 Frequency distribution of qualitative traits in 123 Tanzanian pigeonpea landraces

Trait and category	Frequency (%)	Trait and category	Frequency (%)
Stem color		*Base seed colour*	
Green	97	Cream	94
Purple	3	Dark purple	2
Growth habit		Light grey	2
Erect	2	Light brown	2
Semi-spread	93	*Second seed colour*	
Spread	5	None (plain)	60
Flowering pattern		Light brown	36
Determinate	1	Purple	3
Semi-determinate	40	Reddish brown	1
Indeterminate	59	*Seed colour pattern*	
Base flower colour		Plain	60
Ivory	14	Speckled	33
Light yellow	36	Mottled	3
Yellow	37	Mottled/speckled	4
Red	13	*Seed eye colour*	
Streak pattern		None	67
Sparse	26	Light brown	28
Medium	17	Purple	2
Dense	30	Grey/Dark purple/Cream	2
Plain	27	Reddish brown	1
Second flower colour		*Seed eye width*	
Purple	9	Narrow	25
Red	54	Medium	26
None	37	None	46
Pod colour		Wide	3
Green	29	*Strophiole*	
Purple	5	Present	80
Dark purple	16	None	20
Mixed	50	*Seed shape*	
Pod form		Oval	48
Flat	96	Globular	39
Cylindrical	4	Square	9
Pod hairiness		Elongate	4
Hairy	25		
Non-hairy	75		

streaks (54%), and mixed pods (50%). These results also agree with findings by Upadhyaya et al. (2005).

Our research confirms farmer and market preferences for cream and white seed types as manifested in 94% of the accessions falling in this category (Table 1), and agrees with findings reported by Shiferaw et al. (2005). The frequency of plain white and cream types was however highest in the northern highlands, where the crop is commercialized and preference is for uniform cream and white grain. The mean diversity indices of the assessed qualitative traits in the accessions were generally low (0.2382) and ranged from 0.0436 (stem colour) to 0.4471 (flower streak pattern) (Table 2). Between the four collection regions, diversity indices ranged from 0.1665 (northern highlands) to 0.2749 (coastal zone). There were no significant diversity differences in stem colour, growth habit, base flower colour, pod form, pod hairiness, seed eye colour and seed eye width in the germplasm. Northern highlands landraces had the lowest diversity in all significantly different traits, which is an indication of selection for market preferences.

Quantitative traits

There was a significant GEI variation ($P < 0.05$) among the 14 quantitative traits assessed, and within and between collecting regions (Table 3). There was a wide range of variability in the germplasm in all quantitative traits except seeds per pod at Ilonga.

The lowest mean plant height of 120 cm at Kabete (mean seasonal temperature 18.4°C), compared with Kampi ya Mawe (121 cm) and Ilonga (189 cm) with seasonal mean temperatures of 22.8°C and 24.4°C, respectively agree with earlier findings reported by Silim et al. (1995) that there is reduction in pigeonpea plant height with reduction of temperature during the cropping season. Accessions from the northern highlands were the tallest at all experimental sites and took longer to flower at Kampi ya Mawe (198 days), where mean temperatures are high, than at Kabete (120 days) where mean temperatures are low. Silim et al. (2006) also reported that long duration landraces from the high elevations require low optimum temperature for rapid flowering; thereby experiencing delayed flowering at intermediate elevation and fail to flower at low elevations. Maturity

Table 2 Region-wise mean diversity indices (Ĥ) in the 16 qualitative traits recorded on 123 Tanzanian pigeonpea landraces

Trait	Region				Cumulative mean diversity indices
	Coast	Eastern	Southern	Highlands	
Stem colour	0.0366	0.0420	0.0168	0.0792	0.0436 ± 0.1619
Growth habit	0.1157	0.0901	0.1026	0.0688	0.0943 ± 0.1252
Base flower colour	0.3314	0.2684	0.2533	0.2607	0.2784 ± 0.0618
Flower streak pattern	0.4896	0.5115	0.4968	0.2903	0.4471 ± 0.0717
Second flower colour	0.4156	0.3365	0.4487	0.3409	0.3854 ± 0.0543
Flowering pattern	0.4417	0.3191	0.3949	0.2057	0.3404 ± 0.1218
Pod colour	0.4455	0.473	0.4893	0.1873	0.3988 ± 0.1648
Pod form	0.0630	0.0941	0.0336	0.1061	0.0742 ± 0.0512
Pod hair	0.3466	0.4093	0.4241	0.2203	0.3501 ± 0.1492
Base seed colour	0.0940	0.0466	0.0347	0.0101	0.0464 ± 0.0708
Second seed colour	0.2631	0.2408	0.2353	0.1263	0.2164 ± 0.0663
Seed colour pattern	0.3649	0.3348	0.3421	0.1774	0.3048 ± 0.0806
Seed shape	0.3064	0.3371	0.2967	0.0564	0.2492 ± 0.1388
Seed eye colour	0.1414	0.0944	0.0902	0.1189	0.1112 ± 0.0825
Seed eye width	0.2100	0.2019	0.1906	0.2253	0.2069 ± 0.1614
Strophiole	0.3332	0.3945	0.1360	0.1908	0.2636 ± 0.0916
Mean Ĥ	0.2749 ± 0.2320	0.2621 ± 0.2344	0.2491 ± 0.2205	0.1665 ± 0.3122	0.2382 ± 0.0971

Table 3 Mean, minimum, maximum, standard errors (SE) and *F*-test significance of recorded quantitative traits on 123 Tanzanian pigeonpea landraces at 3 locations

Trait	Kampi Ya Mawe					Kabete					Ilonga				
	Min	Max	Mean	*SE*±	*F*-test	Min	Max	Mean	*SE* ±	*F*-test	Min	Max	Mean	*SE*±	*F*-test
Plant height (cm)	63	220	121	7.597	***	84	256	120	6.188	***	104	265	189	8.062	***
Days 50% flowering	98	262	135	7.398	***	79	164	101	5.483	***	90	151	108	3.370	***
Primary branches per plant	2	22	6	1.444	***	4	21	10	2.210	***	5	22	12	2.409	***
Days 75% maturity	134	284	174	7.303	***	130	252	154	4.818	***	144	193	164	4.684	***
Seeds/pod	5	7	6	0.322	***	4	7	6	0.336	***	4	9	6	0.739	NS
Grain yield (t/ha)	0.007	1.328	0.363	0.084	***	0.107	4.885	2.011	0.625	***	0.067	3.333	1.551	0.370	***
100 seed mass (g)	9.2	22.0	14.6	1.633	***	11.3	20.8	15.9	1.101	***	5.2	19.3	12.9	1.198	***
Secondary branches per plant	1	36	6	1.839	***	2	30	14	3.471	***	–	–	–	–	–
Racemes per plant	11	210	47	4.843	***	41	502	154	37.500	***	–	–	–	–	–
Pod bearing length (cm)	35	167	77	6.248	***	32	90	54	6.146	***	–	–	–	–	–
Pods per plant	25	158	66	6.770	***	26	464	166	44.740	***	–	–	–	–	–
Pod length (cm)	5.3	11.9	8.5	0.667	***	7.3	10.7	8.8	0.663	***	–	–	–	–	–
Pod weight (t/ha)	0.020	2.824	0.740	0.170	***	0.206	9.371	3.414	0.910	***	–	–	–	–	–
Threshing %	29.0	71.8	49.2	4.128	***	34.3	71.0	58.8	4.823	***	–	–	–	–	–
Pod width (cm)	-	-	-	-	-	0.9	1.5	1.1	0.109	***	–	–	–	–	–

*** Highly significant ($P < 0.05$); NS—non-significant

classification of the accessions based on days to maturity (early: <135, medium: 135–160, and late >160 days) placed most of the coastal, eastern and southern landraces in the medium maturity group whereas most of the northern highlands landraces belong to the late maturity group across the experimental sites. The low mean pods per plant at Kampi ya Mawe (66) could be attributed to low moisture supply and high temperature as observed by Turnbull (1986) that at high constant day temperatures, floral abortion increases leading to low pod set. Our research findings reveal a high mean seed mass within the collection (14 g on average) and highlands accessions, which are also late maturing, had the highest mean seed mass (16.2 g) at Kabete—a cooler environment where moisture supply in the cropping season was not limiting. This is similar to findings by Ong and Monteith (1985), who reported that pearl millet produced larger seeds at cooler (low) temperatures because of a longer seed filling duration. On average, coastal, eastern and southern landraces, which are early in maturity, were high yielding at Ilonga and Kampi ya Mawe, where rainfall is low and cropping cycle short, whereas highland collections that are later in maturity showed high yields at Kabete, where rainfall is high and cropping cycles long. The high variability in agronomic traits among the accessions and between accessions and environments indicates the suitability of certain pigeonpea genotypes to specific environments.

Broad-sense heritability

Heritability estimates for days to flowering, days to maturity, grain yield, primary branches, seeds per pod and 100 seed mass, on pooled means across the three sites varied from 0.28 for grain yield to 0.82 for plant heights (Table 4). Heritability estimates help in selection as they isolate the variability due to genotype from the phenotypic variance (Ortiz 1997). Based on classification by Saxena and Sharma (1990), low heritabilities were observed in grain yield (0.28) and seeds per pod (0.4), medium heritabilities in days to maturity (0.67), number of primary branches (0.58) and 100 seed mass (0.63), and high heritabilities in days to flowering (0.75) and plant

Table 4 Quantitative traits variances and heritabilities in 123 Tanzanian pigeonpea landraces

Trait	Genotypic Mean square	G × E Mean square	Error (Environ) Mean square	$V_{(G)}$	$V_{(G \times E)}$	$V_{(P)}$	H
Across Kampi ya Mawe-Kabete							
Days 50% flower	2923.75	1331.13	34.95	265.44	432.06	487.29	0.54
Days 75% maturity	6300.03	2304.22	43.55	665.97	753.56	1050.01	0.63
Plant heights (cm)	3890.80	1065.66	44.10	470.86	340.52	648.47	0.73
Grain yield (t/ha)	1.35	0.76	0.25	0.10	0.17	0.22	0.43
Pod bearing length (cm)	1348.80	1007.81	33.81	56.84	324.67	224.81	0.25
Pod length (cm)	2.15	0.91	0.44	0.21	0.16	0.36	0.58
Pods per plant	5322.00	3106.00	1213.00	369.33	631.00	887.00	0.42
Pod yield (t/ha)	3.99	2.58	0.58	0.23	0.67	0.66	0.35
Primary branches	15.30	8.17	3.90	1.19	1.42	2.55	0.47
Raceme number	15102.90	4668.40	830.60	1739.08	1279.27	2517.15	0.69
Secondary branches	95.88	37.65	8.59	9.70	9.69	15.98	0.61
Seeds/pod	0.29	0.14	0.10	0.03	0.01	0.05	0.54
100 seed weight (g)	11.52	3.42	1.77	1.35	0.55	1.92	0.70
Threshing%	91.91	74.56	45.56	2.89	9.67	15.32	0.19
Across Ilonga-Kampi ya Mawe-Kabete							
Days 50% flower	3029.40	771.27	29.40	250.90	247.29	336.60	0.75
Days 75% maturity	5347.97	1773.28	38.29	397.19	578.33	594.22	0.67
Plant heights (cm)	5267.04	958.58	48.34	478.72	303.41	585.23	0.82
Grain yield (t/ha)	0.82	1.33	0.22	0.06	0.37	0.21	0.28
Primary branches	26.28	10.91	4.71	1.71	2.07	2.92	0.58
Seeds/pod	0.48	0.29	0.20	0.02	0.03	0.05	0.40
100 seed weight (g)	14.35	5.36	1.72	1.00	1.21	1.59	0.63

heights (0.82). Dahiya and Brar (1977) also reported similar varying heritabilities in these traits in pigeonpea. Because traits with high heritabilities are the most reliable as germplasm descriptors (Abu-Alrub et al. 2004), plant height, days to flower, days to maturity and 100 seed mass could be used for pigeonpea germplasm classification.

Principal components and cluster analysis

Specific patterns that defined the way the variables were associated to influence the first four PCs were identified (Tables 5). At the three test sites, PC1, which is the most important, accounted for most of the variability with high positive loadings from days to flower, days to maturity, plant height, pod bearing length, number of primary and secondary branches and pods per plant.

The bi-plot of PC1 and 2 scores distributed the accessions into two major scatter distributions similarly at the three trial sites (Fig. 1). Accessions from northern highlands had strong positive scatter PC1 suggesting that they were tall, late to flower and in maturity, with long pod bearing length, higher number of pods per plant, and a higher number of primary and secondary branches. Collections from the coastal zone, eastern and southern plains tended to cluster together on the lower end of both PC1 and PC2, suggesting that they are generally shorter, early in flowering and maturity, have a fewer number of pods per plant and lower yields. Differential trait loadings on the same PC at different locations was evident in grain yield that had positive loadings on PC1 at Kabete, but had negative loadings on PC1 at both Ilonga and Kampi ya Mawe. This was an indication of a strong influence of environment (moisture in this case) on some traits as earlier reported by Silim et al. (2006) or specific adaptation of cultivars. There was very close dispersion within and among the coastal, eastern and southern landrac-

Table 5 Principal components (PC) on 14 quantitative traits recorded on 123 Tanzanian pigeonpea landraces at individual locations

	PC1	PC2	PC3	PC4
Kabete				
Eigen-value	5.902	1.639	1.371	1.112
Proportion of variance	42.16	11.71	9.80	7.94
Total variance	42.16	53.87	63.67	71.61
Eigen-vectors (loadings)				
Plant heights	0.35574	0.10630	0.17543	0.15884
Days 50% flower	0.36767	−0.04621	0.06162	0.03377
Primary branches	0.25623	0.00842	0.05123	0.22133
Seeds per pod	−0.01646	−0.48368	0.50138	−0.30082
Days to 75% maturity	0.24883	−0.04288	0.01637	−0.10670
Grain yield	0.29983	−.032501	−0.26783	−0.29159
100 seed mass	−0.03686	−0.32780	−0.30290	0.70516
Pod bearing length	0.33769	0.13384	0.15774	0.10828
Pod length	−0.04233	−0.54020	0.40827	0.32750
Pods per plant	0.32070	−0.12885	−0.22099	−0.00221
Secondary branches	0.27792	0.01336	−0.19178	0.13611
Raceme number	0.31784	0.24748	0.15395	0.06152
Pod yield	0.31885	−0.26500	−0.16558	−0.28230
Threshing %	−0.14341	−0.28222	−0.46837	−0.13963
Kampi ya Mawe				
	PC1	PC2	PC3	PC4
Eigen-value	4.355	2.072	1.219	0.983
Proportion of variance	35.69	16.98	9.99	8.05
Total variance	35.69	52.67	62.66	70.71
Eigen-vectors (loadings)				
Plant heights	0.40954	−0.08960	0.06959	−0.07887
Days 50% flower	0.40729	0.07146	0.05854	−0.01317
Primary branches	0.27536	−0.05387	−0.05633	−0.15756
Seeds per pod	−0.28324	0.03143	0.04146	−0.46860
Days to 75% maturity	0.41853	0.05906	0.06244	−0.01402
Grain yield	−0.05936	−0.65248	0.02891	0.12162
100 seed mass	0.22589	−0.25007	−0.25265	−0.01960
Pod bearing length	0.30962	0.03478	0.14592	−0.11023
Pod length	−0.24387	−0.10511	−0.10475	−0.51230

Table 5 continued

Pods per plant	0.10935	−0.15114	0.60919	−0.48973
Secondary branches	0.21654	−0.02136	−0.34956	0.01074
Raceme number	0.24135	−0.06197	−0.01229	−0.14198
Pod yield	−0.06009	−0.63823	0.17174	0.21825
Threshing %	0.06771	−0.21091	−0.60254	−0.38920
Ilonga				
	PC1	PC2	PC3	PC4
Eigen-value	3.939	0.879	0.527	0.397
Proportion of variance	66.04	14.73	8.84	6.65
Total variance	66.04	80.77	89.61	96.26
Eigen-vectors (loadings)				
Plant heights	0.40128	0.05958	−0.67751	−0.37649
Days 50% flower	0.48606	−0.03334	−0.09908	0.15768
Primary branches	0.24955	0.88032	0.34514	−0.20661
Days to 75% maturity	0.47619	−0.02917	−0.19486	0.20325
Grain yield	−0.42628	0.11345	−0.32463	−0.60018
100 seed mass	−0.36328	0.45458	−0.51835	0.62385

es (and separated from northern highlands accessions) and a more wide dispersion within the highland landraces, which reveals a higher similarity among the landraces from coastal, eastern and southern regions. Hierarchical clustering separated the accessions into six clusters with distribution similar to biplot scattering. Clusters 1–4 were mainly composed of accessions collected from the coast, eastern and southern plains and most of the medium-duration check cultivars. Clusters 5 and 6 contained mostly northern highlands landraces and long duration checks.

The delineation of the germplasm into two distinct regions of genetic diversity is similar to findings by Rojas et al. (2000) who studied diversity of Bolivia's quinoa (*Chenopodium quinoa* Willd.) and placed the seven clusters identified into three genetic diversity areas based on altitude. This best explains the two regional classification in our research. The climatic diversity in the three regions of coastal, eastern and southern plains is not wide enough to strongly separate pigeonpea cultivars. It is also possible that years of farmer selection for adaptation to unfavourable weather (drought) could have reduced the

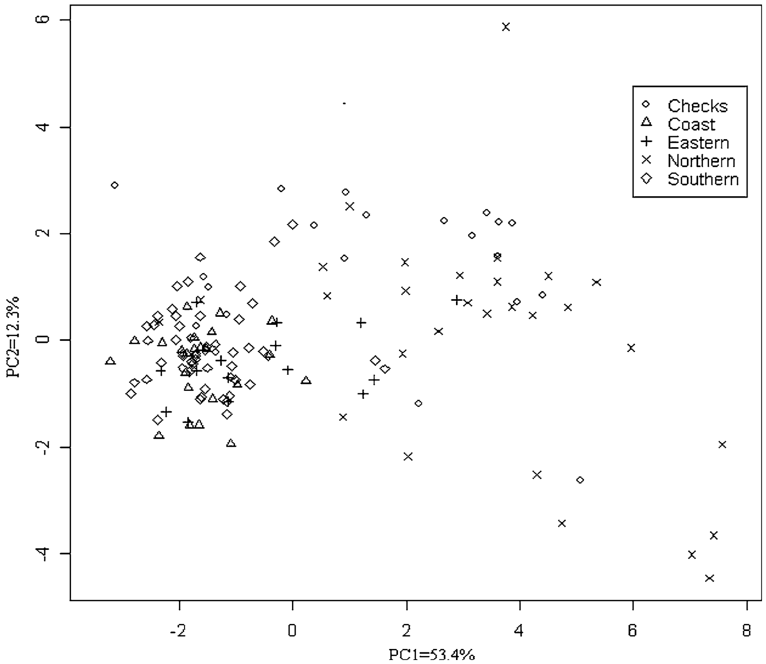

Fig. 1 Scatter diagram for first two principal components (PC1 and PC2) based on 14 quantitative traits recorded at Kabete

diversity in the coastal, eastern and southern regions relative to the northern highlands where moisture is not as limiting. However, as indicated earlier in our research, pigeonpea has a phenological sensitivity to temperature with different temperature requirements for time to flower for different duration types. This sensitivity limits pigeonpea adaptation to diverse altitudes with a definite separation between high and low altitude cultivars (Silim et al. 2006). The adaptation to specific agro-ecologies is confirmed by similarity in clustering where medium-duration checks adapted to low and medium altitudes were clustered with collections from the coastal, eastern and southern plains, and long duration checks clustered with collections from the highlands. Accessions with similar agronomic traits were grouped together irrespective of collection region. Agro-ecological conditions in a given location usually determine farmers' selection strategies. As shown by our research, farmers' selection for desirable agronomic traits is a major determinant in shaping the diversity of the crop's population.

Acknowledgement The authors are grateful to the Danish International Development Agency (DANIDA) for providing funds for this study.

References

Abu-Alrub I, Christiansen JL, Madsen S, Sevilla R, and Ortiz R (2004) Assessing tassel, kernel and ear variation in Peruvian highland maize. Plant Genet Resour Newslett 137: 34–41

Baldev B (1988) Cropping patterns. In: Baldev B, Ramanujam S, Jain HK (eds) Pulse crops. Oxford and IBH Publishing Co. Pvt. Ltd, New Delhi, India, pp 513–557

Dahiya BS, Brar JS (1977) Diallel analysis of genetic variation in pigeonpea *Cajanus cajan* (L.) Millsp. Exp Agric 13(2):193–200

Fundora Mayor Z, Hernandez M, Lopez R, Fernandez L, Sanchez A, Lopez J, Ravelo I (2004) Analysis of the variability in collected peanut (*Arachis hypogaea* L.) cultivars for the establishment of core collections. Plant Genet Resour Newslett 137:9–13

Haryanto TAD (2002) Procedures for estimating values, genetic correlations and combining abilities of several agronomic characters.www.dl.dion.ne.jp/~tmhk/yosida. Internet

Hodgkin T (1997) Some current issues in conservation of plant genetic resources. In: Ayad WG, Hodgkin T, Jaradat A, Rao VR (eds) Molecular genetic techniques for plant genetic resources. Report of an IPGRI workshop 9–11 October 1995, Rome, Italy, pp 3–10

IBPGR and ICRISAT (1993) Descriptors for pigeonpea (*Cajanus cajan* (L) Millsp). International Board for Plant Genetic Resources, Rome, Italy; International Crops Research Institute for the Semi-Arid tropics, Patancheru, India

Jain SK, Qualset CO, Bhatt GM, Wu KK (1975) Geographic patterns of phenotypic diversity in a world collection of durum wheats. Crop Sci 15:700–704

Kaiser HF (1960) The application of electronic computers to factor analysis. Educ Psychol Meas 20:141–151

Mead R, Curnow RN, Hasted AM (2002) Statistical methods in agriculture and experimental biology, 3rd edn. Chapman and Hall/CRC. pp. 406–418. (Texts in Statistical Science Series)

Ogunbodede BA (1997) Multivariate analysis of genetic diversity in Kenaf, *Hibiscus cannabinus* (L.). Afr Crop Sci J 5(2):127–133

Ong CK, Monteith JL (1985) Response of pearl millet to light and temperature. Field Crop Res 11:141–160

Ortiz R (1997) Morphological variation in *Musa* germplasm. Genet Resour Crop Evol 44:393–404

Rojas W, Barriga P, Figueroa H (2000) Multivariate analysis of the genetic diversity of Bolivian quinua germplasm. Plant Genet Resour Newslett 122:16–23

Saxena KB, Sharma D (1990) Pigeonpea: Genetics. In: Nene YL, Hall SD and Sheila VK (eds) The Pigeonpea. Wallingford, UK: CAB International, pp 137–157

Shiferaw B, Silim SN, Muricho G, Audi P, Mligo J, Lyimo S, Liangzhi Y, Christiansen JL (2005) Assessment of the adoption and impact of improved pigeonpea cultivars in Tanzania. Working paper series no. 21. Patacheru 502 324, A.P. India. ICRISAT, pp 1–24

Silim SN, Omanga PA, Johansen C, Singh, L, Kimani PM (1995) Use of the Kenya transect for selecting and targeting adapted cultivars to appropriate production systems. In: Silim SN, King SB, Tuwafe S (eds) Proceedings of improvement of pigeonpea in Eastern and Southern Africa—Annual research planning meeting 1994, 21–23 Sep 1994, Nairobi, Kenya. Patancheru 502 324, A.P., India. ICRISAT. 220 pp. ISBN 92–9066–316-2, pp 44–54

Silim SN, Bramel PJ, Akonaay HB, Mligo JK, Christiansen JL (2005) Cropping systems, uses, and primary in situ characterization of Tanzanian pigeonpea (*Cajanus cajan* (L.) Millsp.) landraces. Genet Resour Crop Evol 52:645–654

Silim SN, Coe R, Omanga PA, Gwata ET (2006) The response of pigeonpea genotypes of different types to variation in temperature and photoperiod under field conditions in Kenya. J Food Agric Environ 4(1):209–214

Turnbull LV (1986) The role of photoperiod and temperature in early vegetative growth and floral development in selected lines of pigeonpea (*Cajanus cajan* (L.) Millsp.). PhD thesis, University of Queensland, Australia, 309 pp

Upadhyaya HD, Pundir RPS, Gowda CL, Reddy KN, Singh S (2005) Geographical patterns of diversity for qualitative and quantitative traits in the pigeonpea germplasm collection. Plant Genet Resour 3(3):331–352

Whiteman PC, Byth DE, Wallis ES (1985) Pigeonpea (*Cajanus cajan* (L.) Millsp.). In: Summerfield RJ, Roberts EH (eds) Grain legume crops. Collins Professional and Technical Books, London, pp 658–698