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Stratification of SADC regional sorghum testing sites based on grain yield of varieties

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Abstract

We applied sequential retrospective (SeqRet) pattern analysis to stratify sorghum variety testing sites according to their similarity for yield discrimination among genotypes using historical grain yield data from 147 multi-environment trials (METs). The trials were conducted at 38 sites in 10 countries of the Southern African Development Community (SADC) region during 1987/1988–1992/1993 and 1999/2000. The analysis for the 6 years 1987/1988–1992/1993, covering 34 sites, clustered these sites into 6 major groups with a model fit of $R^2 = 0.75$. With additional data from the year 1999/2000, the SeqRet pattern analysis delivered a very similar clustering of the 34 sites, with the additional four sites in 1999/2000 properly classified with appropriate site groups ($R^2 = 0.74$). The results suggest that future sorghum variety testing could be restricted to a few representative sites selected from within each of the six identified site-groups.

Keywords: Sorghum; Site stratification; Sequential retrospective pattern analysis

1. Introduction

The presence of large crossover genotype-by-environment interactions (GEI) for polygenic traits like grain yield is a serious limiting factor in accurately selecting high yielding genotypes for maximizing crop productivity in a targeted production area. It may however be possible to exploit GEI for achieving increased progress from selection if representative subsets of test environments in the target area could be identified, such that the environments within each subset generate a similar long-term repeatable pattern of discrimination among genotypes that could be associated with some known or expected environmental factor(s). Such grouping of test environments increases genetic correlation among environments within groups and leads to a more accurate and confident identification of high yielding genotypes suitable for each group of environments in the target area. Yield data from long-term historical multi-environment trials (METs) offer a unique opportunity to identify any such groups of test environments reflecting long-term repeatable patterns in GEI in the target population of environments. Such information is also useful for designing efficient and cost-effective regionalized plant breeding strategies.

The Southern African Development Community (SADC) region represents a large geographic region spread over 14 southern Africa countries. Stratification of test environments in the SADC region could help in choosing appropriate future testing sites and in objective targeting of varieties for maximizing production (Peterson, 1992). This paper reports the stratification of sorghum variety testing sites, and its implications, in the SADC region as obtained from application of sequential retrospective (SeqRet) pattern analysis using highly unbalanced historical and recent grain yield data. This paper, after Mgonja et al. (2002), is the

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second one in a series aimed at exploiting the available long-term historical data from METs conducted on pearl millet and sorghum in the SADC region.

2. Materials and methods

2.1. Structure and history of field trials

The USAID-supported Sorghum and Millet Improvement Program (SMIP) of ICRISAT was initiated in 1983 as a major crop improvement endeavor for the SADC region with the aim of developing improved sorghum and millet varieties for the drought-prone areas. The present investigation included grain yield data from 147 sorghum METs conducted over a period of 6 years during 1987/1988–1992/1993 covering 34 testing sites and during 1999–2000 covering four additional testing sites. In the process of identifying suitable lines for recommendation to farmers, the number and composition of varieties as well as test-sites were changed over years. Elite lines were often tested for 2–3 years across a range of locations in regional trials to select promising lines for subsequent stages of evaluation.

The regional testing sites were selected primarily on the basis of their proximity to the major sorghum growing areas in the SADC region. The number of testing sites in a country was mainly determined by the importance of the crop and the strength of its national research program. Sorghum growing areas in the SADC region fall under four broad agro-ecosystems (AES) derived mainly on the basis of their length of growing period (LGP): (a) short season, often drought stricken, less than 3 months growing season; (b) warm humid, less than 4 months growing season; (c) cool nights as a result of high altitude; and (d) long growing season (more than 4 months), sporadic and unreliable rainfall. Within each AES, there exists a diversity of soil types, soil texture, and soil water holding properties. Table 1 presents the major biophysical characteristics of the testing sites.

Genetic materials consisted of introduced accessions and elite varieties derived from crossbred sorghum materials (lines, varieties, and composite populations) particularly developed to suit the southern Africa region. The trials were laid out in randomized complete block designs (RCBD) with the number of varieties ranging from 8 to 36 with 3 to 4 replications. Individual plots were arranged in 2 to 6 rows, each 5 m long and spaced 75 cm apart with a plant-to-plant spacing of 15 cm. Net plots of size 4 m × 1.5 m were harvested for yield determination.

2.2. Biometric analysis

The 147 METs were individually analyzed as per design to obtain least squares (LS) estimates of variety means. These 147 METs represented 95 unique site-year environments since at many sites the collaborators, in order to test more genetic materials, simultaneously conducted two or more trials in nearby fields in one or more years with or without common varieties. At all of these 'multiple-trial' sites, the error mean squares in the trials were found to be homogeneous ($P > 0.05$) as indicated by Bartlett's test (Kanji, 1993), except that six trials (one, out of the two/three trials, at Makoholi and Matopos in 1987/1988, at Maseru in 1989/1990, at Kasintula in 1990/1991, and at Ngabu and Pandamatenga in 1992/1993) had excessively high error mean square and, therefore, were dropped from the analysis, leaving 89 site-year environments for analysis. This provided a basis to treat the multiple trials in nearby fields at a site as if they were a single trial, with performance of any common variety determined as the ordinary mean of its LS mean estimates in the trials. A similar approach was followed in Mgonja et al. (2002).

Sequential retrospective (SeqRet) pattern analysis (DeLacy et al., 1996), as outlined in Mgonja et al. (2002), was applied to the mean data y_{ijk}, derived as above, from the 89 unique site-year environments for variety $k = 1, \ldots, \delta_{ij}$ at site $i = 1, \ldots, n_1$ in year $j = 1, \ldots, \gamma_i$, where δ_{ij} is the number of varieties tested in (i, j)th site-year environment, n_1 is the number of sites, and γ_i is the number of years in which site i was present. The δ_{ij} varieties grown in the (i, j)th site-year environment were considered to be a random (representative) sample of all test varieties. This is an appropriate assumption to investigate the similarity among testing sites for selection purposes (DeLacy et al., 1996). The necessary computations were carried out using the SEQRET package version 1.1 (DeLacy et al., 1998). The adequacy of a site-stratification model was judged on the basis of the R^2-statistic (DeLacy et al., 1996). A site-stratification model with $R^2 \geq 0.70$ was considered as adequate (Mgonja et al., 2002).

The 7 years' data were analyzed in two ways: set 1 (1987/1988–1992/1993) spanning 6 years and 34 sites, set 2 (1987/1988–1992/1993, 1999/2000) spanning 7 years and 38 sites, the latter having a gap of 7 years. In set 1, Lucydale and Lucydale1, Makoholi and Makoholi1, and Matopos and Matopos1 were treated as different sites as the two trials at each of these three sites substantially differed in terms of their cumulative rainfall during the cropping season and dates of planting and harvesting. The sites Lucydale, Makoholi and Matopos represent trials managed by ICRISAT, whereas Lucydale1, Makoholi1 and Matopos1 represent trials that were managed by NARS at these sites. The above analytical approach was applied separately on each data set to assess the stability/consistency, or the lack of it, in inter-site relationships as a result of superimposing the data from the year 1999/2000 on data from the years 1987/1988–1992/1993.

3. Results

Set 1 (1987/1988–1992/1993) contained 34 sites across the 6 years. The SeqRet analysis retained 12 sites, with 22

Table 1
Biophysical characteristics of SADC[a] sorghum variety testing sites

Site (code)	Country	Soil type[b]	SWHC[c]	PH	Drainage[d]	Longitude	Latitude	Altitude (m)	Annual rainfall (mm)	First month[e]	Minimum temperature (°C)	Maximum temperature (°C)	LGP[f]	Site group
Luanda (lua)	Angola	C	M	6.4	H	13.2	−8.9	40	374	12	22	27	2	5
Good Hope (qco)	Botswana	C/M	VL	6.3	MWD	25.5	−25.5	1232	500	3	11	27	1	4
Sebele (seb)	Botswana	C	VL	6.4	ED	26.0	−24.6	976	495	11	12	28	2	4
Pandamatenqa (pand)	Botswana	M/F	H	6.4	MD	25.7	−18.3	1070	671	12	14	30	4	4
Maseru (mas)	Lesotho	M/F	L	6.2	WD	27.6	−29.5	1501	669	12	8	23	4	2
Ngabu (nga)	Malawi	F	H	7.3	ID	34.9	−16.5	115	760	11	19	32	4	5
Kasintula (has)	Malawi	F	M	6.6	PD	34.8	−16.1	122	793	12	19	32	4	4
Makoka (mako)	Malawi	M	VL	7.1	WD	35.2	−15.2	650	885	11	18	28	5	5
Chokwe (cho)	Mozambique	F	M	6.8	PD	33.0	−24.5	33	646	11	17	31	4	2
Chimoio (chim)	Mozambique	M/F	L	5.1	WD	33.5	−19.1	610	1106	11	16	26	5	1
Umbeluzi (umb)	Mozambique	M	H	6.4	WD	32.3	−26.0	64	667	12	17	29	5	4
Nampula (nam)	Mozambique	M/F	VL	6.4	WD	39.3	−15.1	329	1045	10	19	31	5	2
Mashare (mash)	Namibia	M	M	6.6	ID	20.2	−17.9	1061	568	1	14	31	4	4
Mahanene (man)	Namibia	C	H	6.4	WD	15.2	−17.5	1110	505	11	13	29	3	4
Okashana (oka)	Namibia	C	H	8.5	WD	16.5	−18.3	1097	446	1	15	31	3	4
Luve (luv)	Swaziland	F	L	5.1	WD	31.2	−26.3	986	982	10	12	24	7	3
Nhlanqano (nhl)	Swaziland	F	L	5.1	WD	31.1	−27.1	993	855	10	13	25	7	3
Malkerns (mal)	Swaziland	M/F	H	6.2	WD	31.2	−26.6	763	890	12	13	26	7	3
Bigbend (ben)	Swaziland	F	L	5.7	ID	32.0	−26.8	102	593	12	16	29	4	2
llonqa (ilo)	Tanzania	F	L	5.7	WD	37.0	−6.8	914	978	11	16	28	6	6
Ukiriguru (uki)	Tanzania	C/M	M	5.4	ID	33.0	−2.7	1239	952	11	17	28	7	4
Hombolo (hom)	Tanzania	C/M	M	5.4	MD	35.9	−6.0	1019	562	12	16	30	4	2
Tumbi (turn)	Tanzania	C/M	M	5.1	MWD	32.5	−5.1	1222	935	11	16	29	6	3
Naliendele (nal)	Tanzania	C/M	L	5.1	WD	38.8	−10.4	383	876	2	20	31	5	2
Mt Makulu (mou)	Zambia	M/F	L	5.1	ID	32.6	−9.4	1463	1053	1	15	28	6	2
Golden Valley (gol)	Zambia	M/F	H	6.4	MWD	28.1	−14.9	1189	909	11	14	27	5	6
Lusitu (lus)	Zambia	C	H	6.4	WD	28.8	−16.1	326	632	11	19	32	3	5
Matopos (mat)	Zimbabwe	F	H	6.4	MD	28.5	−20.4	1416	591	11	12	25	4	3
Makoholi (mak)	Zimbabwe	M	M	6.4	MWD	30.8	−19.8	1111	628	12	13	26	5	3
Kadoma (kad)	Zimbabwe	F	H	6.3	MWD	29.9	−18.3	1107	735	12	14	28	5	1
Lucydale (luc)	Zimbabwe	F	H	6.4	MD	28.5	−20.4	1416	591	11	12	25	4	1
Chiredzi (chir)	Zimbabwe	C/M	M	6.4	WD	31.7	−21.1	388	544	11	15	30	3	2
Muzarabani (muz)	Zimbabwe	M	H	6.4	MWD	31.0	−16.4	427	665	12	17	32	3	5
Gwebi (gwe)	Zimbabwe	C	H	6.1	ID	30.8	−17.7	1418	831	11	11	26	5	2
Panmure (pan)	Zimbabwe	M	M	6	MWD	31.6	−17.3	1037	817	11	13	27	5	2

[a] Southern Africa Development Community.
[b] M: medium; F: fine; C: course.
[c] Soil water holding capacity; H: high; M: medium; L: low; VL: very low.
[d] WD: well drained, ID: imperfectly drained; MD: moderately drained; MWD: moderately well drained; PD: poorly drained; ED: excessively drained; SED: somewhat excessiveiy drained.
[e] Officially declared month for beginning of planting.
[f] Length of growing period.

sites eliminated due to lack of comparisons. A clustering of these 34 sites into six groups (Fig. 1), with the 22 eliminated sites assigned to site groups with the nearest centroid, delivered a model fit of $R^2 = 0.75$. The six groups were grp1 = {Matopos, Makoholi, Luve, Malkerns, Matopos1, Nhlangano, Tumbi}, grp2 = {Lucydale, Kadoma, Chimoio}, grp3 = {Sebele, Kasintula, Pandamatenga, Good Hope, Mahanene, Ukiriguru, Umbeluzi}, grp4 = {Hombolo, Bigbend, Chiredzi, Chokwe, Gwebi, Lucydale1, Makoholi1, Maseru, Mt Makulu, Panmure}, grp5 = {Ngabu, Muzarabani, Luanda, Makoka, Lusitu}, and grp6 = {Ilonga, Golden Valley}.

Set 2 (1987/1988–1992/1993, 1999/2000) contained 38 sites across the 7 years, 34 sites being the same as in set 1. The cumulative analysis retained 12 sites. The remaining 26 sites were eliminated due to lack of comparisons. A clustering of these 38 sites into six groups (Fig. 2), with the 26 eliminated sites assigned to site groups with nearest centroid, provided a model fit of $R^2 = 0.74$. The six groups were grp1 = {Lucydale, Kadoma, Chimoio, Matopos1},

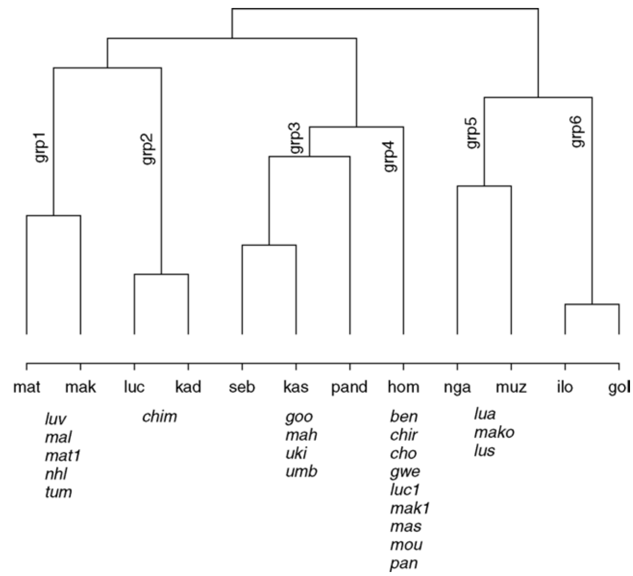

Fig. 1. Dendrogram of cumulative classification of 34 sites based on grain yield per hectare of sorghum varieties planted during 1987/1988–1992/1993 using weighted environment-standardized squared Euclidean distance as dissimilarity measure and incremental sum of squares as clustering strategy. Site codes in Table 1. Italics indicate the sites added to site groups based on nearest centroid criterion.

grp2 = {Hombolo, Bigbend, Chiredzi, Chokwe, Gwebi, Lucydale1, Makoholi1, Maseru, Mt Makulu, Panmure, Naliendele, Nampula}, grp3 = {Matopos, Makoholi, Luve, Malkerns, Nhlangano, Tumbi}, grp4 = {Sebele, Kasintula,

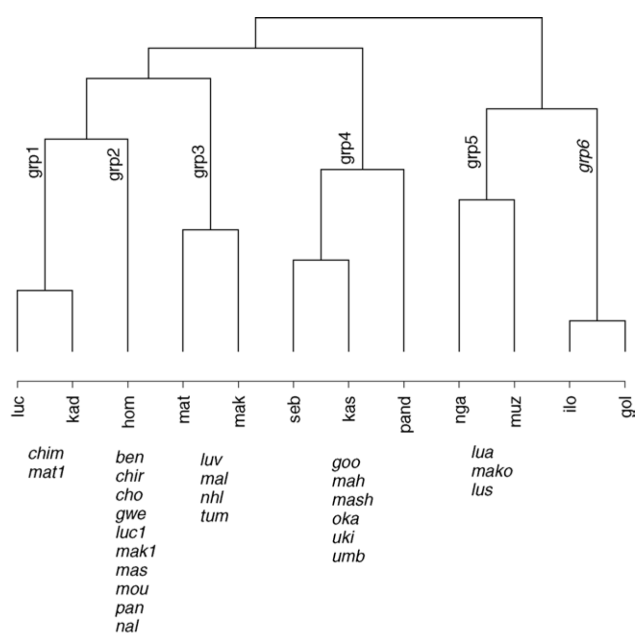

Fig. 2. Dendrogram for cumulative classification of 38 sites based on grain yield per hectare of sorghum varieties planted during 1987/1988–1992/1993 and 1999/2000 using weighted environment-standardized squared Euclidean distance as dissimilaritty measure and incremental sum of squares as clustering strategy. Site codes in Table 1. Italics indicate sites added to site-groups based on nearest centroid criterion.

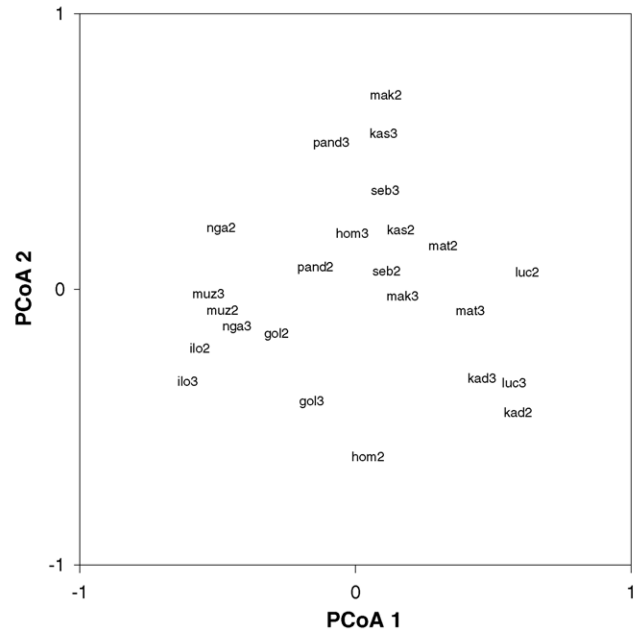

Fig. 3. Proximity plot of first two vectors from cumulative pincipal cooordinate analysis (PCoA) of 24 site-year combinations (corresponding to 12 sites) based on grain yield per hectare of sorghum varieties planted during 1987/1988–1992/1993 using environment-standardized squared Euclidean distance as dissimilarity measurre. Site codes in Table 1. kad2, kad3 stand for kad-1992, kad-1993, etc.

Pandamatenga, Good Hope, Mahanene, Mashare, Okashana, Ukiriguru, Umbeluzi}, grp5 = {Ngabu, Muzarabani, Luanda, Makoka, Lusitu}, and grp6 = {Ilonga, Golden Valley}.

The site grouping in set 2 (Fig. 2) remained nearly the same as in set 1 (Fig. 1). Thus, despite a break of 7 years, the site grouping obtained in set 1 remained relatively stable after taking into account the recent data from year 1999 to 2000.

The proximity plots of the site-year environments for set 1 (Fig. 3) and set 2 (Fig. 4) clearly establish that, as more years' data were added to the SeqRet analysis, the relative positions of the sites in the Euclidean space converged to fixed positions. The convergence was more marked when data from year 1999/2000 was added to data in set 1 (Fig. 4).

Lucydale1 and Makoholi1 (NARS managed sites) consistently grouped separately from Lucydale and Makoholi (ICRISAT managed sites). In the case of Matopos, it grouped together with Matopos1 in set 1 but not in set 2.

4. Discussion

The stratification analysis for the two sets of data partitioned the testing sites into six groups each for set 1 (1987/1988–1992/1993) and set 2 (1987–1999/2000) with $R^2 = 0.75$ and 0.74, respectively. The site groupings in set 2 (Fig. 2) remained almost the same as in set 1 (Fig. 1) despite the addition of year 1999/2000 sites after a 7-year gap. This

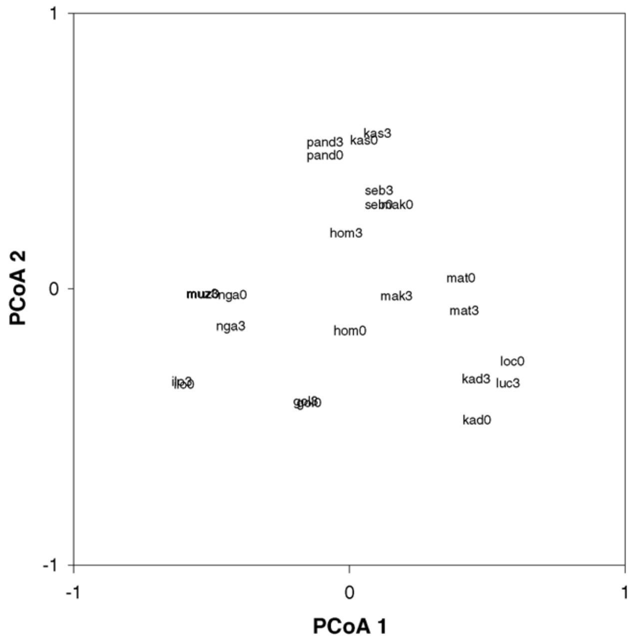

Fig. 4. Proximity plot of first two vectors from cumulative PCoA of 24 site-year combinations (corresponding to 12 sites) based on grain yield per hectare of sorghum varieties planted during 1987/1988–1992/1993 and 1999/2000 using weighted environment-standardized squared Euclidean distance as dissimilarity measure. Site codes in Table 1. kad3, kad0 stand for kad-1993, kad-2000, etc.

implies that by the sixth season, the site stratification seemed to have nearly stabilized. The discussion below is, therefore, based on the site grouping obtained in set 2.

The sites Sebele, Kasintula, Pandamatenga, Good Hope, Mahanene, Ukiriguru and Umbeluzi stratified together with an addition of two short season testing sites, Mashare and Okashana after inclusion of the year 1999/2000 data. Except for Ukiriguru and Umbeluzi, all are characterized by warm short season (3–4 months LGP) often drought stricken environment with erratic rainfall. Sorghum planting at Ukiriguru and Umbeluzi is delayed in preference for other crops, such as cotton and maize, which require full use of the season. The effective season is, therefore, less than the reported LGPs and hence, they get grouped with the short to medium season sites.

The clustering of Sebele and Pandamatenga sites together is an unexpected outcome as they represent quite different and distinct types of environmental conditions. However, a separate analysis of data from these two locations showed that there was little genotype × location interaction ($P > 0.05$) within years, which justifies their clustering together in a single group. Sebele endures continuous drought stress during the early seedling stage and a prolonged terminal drought stress, whereas in Pandamatenga the crop suffers continuous water logging during the early seedling stage and terminal drought stress similar to the one experienced in Sebele. It seems logical to speculate that the crop's reaction to the early seedling episodes of continuous drought stress at Sebele and water logging stress at Pandamatenga produces the same effects on the crop's growth and development, thereby classifying these locations as similar.

The grouping of Hombolo with Bigbend, Chiredzi, Chokwe, Gwebi, Lucydale1, Makoholi1, Maseru, Mount Makulu and Panmure also included Naliendele and Nampula after adding the year 1999/2000 data. Most sites in this group are characterized by medium season (4–5 months LGP). Though similar in the way they discriminate among genotypes, sites in this group can logically be subdivided into two subgroups. The first sub-group includes Mount Makulu, Panmure, Maseru, Gwebi and Hombolo as high altitude sites (1000–1500 masl) with relatively high rainfall (560–1000 mm). Another sub-group for the low altitude sites (30–400 masl) includes Naliendele, Nampula, Chokwe, and Chiredzi. The explanation for the inclusion of the two normally long season sites, Naliendele and Nampula (5–6 months LGP), with the medium season sites is that planting of trials is always delayed: the season starts in October in Nampula but sorghum trials can be planted as late as January, effectively 2 months late, and the season begins in December at Naliendele but trials are planted as late as end of February, effectively 1 month late to avoid grain molding at maturity. It is with this understanding that the breeding programs aimed at developing early maturing materials targeting the short season drought prone areas of the SADC region.

Ilonga and Golden Valley were stratified together. They are both long season (5–6 LGPs) and high altitude sites justifying their own independent grouping. Ngabu, Muzarabani, Luanda, Makoka and Lusitu grouped together in both the sets. These are low altitude (115–650 masl), short season, warm and humid sites. Similar observations were made from the SADC Pearl millet testing sites' stratification (Mgonja et al., 2002).

The grouping together of Matopos, Makoholi, Luve, Malkerns, Nhlangano, and Tumbi can be explained by the fact that they are characterized by cool nights due to high altitudes (763–1416 masl).

Lucydale, Kadoma, and Chimoio are sites with fine to moderately fine textured and moderately well drained soils. Despite the proximity of Lucydale and Matopos, the two stratified separately. This coincides with a known difference in soil types associated with these locations. Lucydale has a generally sandy loam soil, with high water holding capacity attributed to by a high water table; whereas Matopos is characterized by clay loam soils. DeLacy et al. (1996) have also reported this differentiation of sites based on soil types. Similar observations have also been made with reference to these two sites by Mgonja et al. (2002).

The site grouping in set 2 (Fig. 2) remained nearly the same as in set 1(Fig. 1) despite a break of 7 years after taking into account the recent data from the year 1999/2000. This is further supported by more convergence of the sites from the 6-year proximity plots (Fig. 3) to the 7 years proximity plots (Fig. 4).

5. Conclusions

In the face of continually diminishing resources, there is an increasing need to limit the number of testing sites to a level that may allow reliable identification of promising genotypes for maximizing crop productivity in targeted agro-ecological zones of interest. A major step to achieve this goal is to stratify the testing sites into groups in a way that minimizes the within-group $G \times E$ interaction. The application of SeqRet pattern analysis methodology on grain yield data from historical METs stratified the 38 SADC region sorghum variety testing sites, representing 35 distinct locations (Table 1), into six major groups:

Group 1: *Lucydale*, *Kadoma*, *Chimoio*;
Group 2: *Hombolo*, *Bigbend*, *Chiredzi*, *Chokwe*, *Gwebi*, *Maseru*, *Mt Makulu*, *Panmure*, *Naliendele*, *Nampula*;
Group 3: *Matopos*, *Makoholi*, *Luve*, *Malkerns*, *Nhlangano*, *Tumbi*;
Group 4: *Sebele*, *Kasintula*, *Pandamatenga*, *Good Hope*, *Mahanene*, *Mashare*, *Okashana*, *Ukiriguru*, *Umbeluzi*;
Group 5: *Ngabu*, *Muzarabani*, *Luanda*, *Makoka*, *Lusitu*; and
Group 6: *Ilonga*, *Golden Valley.*

This grouping provides an objective basis to choose a small representative subset of testing sites for future targeting of sorghum germplasm in the SADC region to increase breeding efficiency and maximize selection gains in pursuance of breeding for specific adaptation. This will also significantly contribute to faster release of new improved varieties and in increasing the efficiency of supply and delivery of seed for relief purposes.

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