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DIVERSITY AND SPATIAL DISTRIBUTION OF SORGHUM ON FARMERS' FIELDS IN UGANDA

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ABSTRACT

Sorghum (*Sorghum bicolor* (L.) Moench) is a food security crop in sub-Saharan Africa, which requires constant breeding in response to changes in the fragility of agricultural production environments. Hence, understanding and tenacious use of genetic variation in sorghum germplasm is essential for improving the crop to cope with environmental changes. The objective of this study was to determine the levels of diversity and spatial distribution of sorghum on farmers' fields in major sorghum growing regions in Uganda. A survey involving 180 fields was conducted in three districts, namely Agago and Apac (northern) and Serere (eastern) all in Uganda. Diversity was measured in terms of number of accessions per field, the Shannon-Weaver and Simpson diversity indices. In order to assess spatial distribution of sorghum diversity on the fields, correlation analysis was carried out between diversity and geographical distances between fields. Overall, Agago district had the highest number of accessions per unit area (4.47); while Apac had the lowest (1.62). The spatial distribution of sorghum diversity showed a positive correlation ($r = 0.381$ for Agago, 0.124 for Apac and 0.081 for Serere), between geographical distances and diversity across the three districts; implying that fields close together share similar sorghum varieties. This can be due to sharing seeds between farmers within a given location. Sorghum diversity was spatially distributed in the fields, with fields close to each other shared most sorghum types. The levels of sorghum diversity on fields were highest in Agago and lowest in Apac district. The existing on-farm sorghum diversity offers the opportunity for improving sorghum through natural breeding against biotic and abiotic stresses.

Key Words: Diversity indices, geographical distances, *Sorghum bicolor*

RÉSUMÉ

Le sorgho (*Sorghum bicolor* (L.) Moench) est une culture de sécurité alimentaire en Afrique subsaharienne, qui nécessite une sélection constante en réponse à l'évolution de la fragilité des environnements de production agricole. Par conséquent, la compréhension et l'utilisation tenace de la variation génétique dans le matériel génétique du sorgho sont essentielles pour améliorer la culture afin de faire face aux changements environnementaux. L'objectif de cette étude était de déterminer les niveaux de diversité et de distribution spatiale du sorgho sur les champs des agriculteurs dans les principales régions productrices de sorgho en Ouganda. Une enquête portant sur 180 champs a été menée dans trois districts, à savoir Agago et Apac (Nord) et Serere (Est) en Ouganda. La diversité a été mesurée en termes de nombre d'accessions par champ, les indices de diversité Shannon-Weaver et Simpson. Afin d'évaluer la distribution spatiale de la diversité du sorgho sur les champs, une analyse de corrélation a été effectuée entre la diversité et les distances géographiques entre les champs. Dans l'ensemble, le district d'Agago avait le plus grand nombre d'accessions par unité de surface (4,47) ; tandis qu'Apac avait le plus bas (1,62). La distribution spatiale de la diversité du sorgho a montré une corrélation positive (r = 0,381 pour Agago, 0,124 pour Apac et 0,081 pour Serere), entre les distances géographiques et la diversité dans les trois districts ; ce qui implique que les champs rapprochés partagent des variétés de sorgho similaires. Cela peut être dû au partage de semences entre agriculteurs dans un lieu donné. La diversité du sorgho était répartie dans l'espace dans les champs, les champs proches les uns des autres partageant la plupart des types de sorgho. Les niveaux de diversité du sorgho dans les champs étaient les plus élevés à Agago et les plus bas dans le district d'Apac. La diversité existante du sorgho à la ferme offre la possibilité d'améliorer le sorgho grâce à la sélection naturelle contre les stress biotiques et abiotiques.

Mots Clés : Indices de diversité, distances géographiques, *Sorghum bicolor*

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is among the principal cereal crops in the semi-arid tropics, because of its adaptation to a wide range of ecological and climatic conditions (Ali *et al.,* 2011). It is a staple for over 500 million resource-poor farmers in marginal environments; areas often marked by erosion, salinisation and/or low soil fertility (Sher *et al*., 2013). Worldwide, sorghum production was estimated at 62 million metric tonnes annually in 2021, with United States of America producing 11.4 million metric tonnes and Nigeria producing about 6.8 million metric tonnes per year (FAOSTAT, 2022). In Uganda, sorghum is the third most important staple cereal crop mainly grown by the resource poor farmers in semi-arid regions (Olupot, 2011).

Many traditional sorghum varieties (local landraces) have been lost due to modern agricultural practices, such as replacement with improved varieties, leading to reduction in genetic diversity within primary gene pools (Ngugi and Maswili, 2010). The impact in the form of genetic erosion has occasionally been witnessed when calamities strike, such as the ug99 fungal disease threatening wheat production globally; following breakdown in resistance to stem rust (Joshi *et al*., 2008).

Crop genetic diversity forms a foundation for sustainable agriculture and global food security, for crops used in traditional farming systems, conventional breeding or in new biotechnologies (FAO, 1998). If diversity for crops such as sorghum is not well understood and managed, especially on the farmers' fields, there is a high risk of total genetic erosion. Erosion of these resources results in severe threats to the world's long term food security (Hammer *et al*., 1999). Since sorghum is an important cereal cultivated in marginal environments, its genetic diversity is important for improvement of the crop (Westengen *et al*., 2014).

Increasing knowledge on sorghum diversity and distribution on farmers' fields is crucial for the conservation and improvement of sorghum. Without knowledge on sorghum diversity and its distribution on farm, we risk losing diversity to different agents of genetic erosion. Therefore, establishing the spatial distribution of sorghum diversity on farmers' fields will help assess the state of vulnerability, and propose conservation plans to safeguard the threatened species from erosion. There is limited information in relation to on-farm diversity and spatial distribution of sorghum in the major growing areas in Uganda.

Previous studies, for example by Akatwijuka *et al.* (2016) focused on a few landraces grown in the south western part of Uganda. In addition, Mbeyegala *et al.* (2012) only sampled two panicles per field, probably leaving out other accessions there present. The objective of this study was to determine the levels of diversity and spatial distribution of sorghum accessions on farmers' fields in major sorghum growing regions in Uganda.

MATERIALS AND METHODS

Study areas. The study was carried out in three districts of Agago and Apac (Northern), and Serere (Eastern) in Uganda. These districts were purposively selected to represent parts of Uganda where sorghum is the main food security crop (Shively and Hao, 2012).

Agago is situated at latitudes 02^o 50'N and longitudes 33^o 20'E, at an elevation of 1060 m above sea level; while Apac is located at latitudes 02^o 50'N and longitudes 32^{o}32'E , at an elevation of 1020 m asl in Northern Uganda. Serere district is located in the eastern at latitudes 10^o 31'N and longitudes 33^o 33'E, with an elevation of 1038 m asl.

Sampling procedure. In each of the three districts, two sub-counties were purposively selected based on density of households growing sorghum (based on preliminary survey). These included Paimol and Parabongo in Agago, Ibuje and Chegere in Apac and Kateta and Olio in Serere. From each sub-county, two villages were randomly selected. A total of 10 farm households were selected from each two villages, using simple random sampling method. The Sampling frame was a list of households provided by the Local Council I of each village. From each farm household, one sorghum field was selected randomly (in cases where a household has more than one sorghum field) for this study. In total, therefore, 180 fields were sampled, representing 60 fields per district.

The fields sample size was determined using the formula developed by Israel (1992).

$$n = \frac{\left(Z_{\alpha/2} * Z - score\right)^2 * \sigma * (1-\sigma)}{(E)^2}$$

Where:

n is the sample size, $Z_{\alpha/2} = 1.645$ is the score at 90% confidence level two-tail, σ is the standard deviation (calculated at proportion 50%), and E (6.1%) is the margin of error.

$n= (1.645)^2 * 0.5*(1-0.5) / (0.061)^2$
n=181

Data collection. The survey was conducted at different growth stages of the sorghum crop, from flowering to harvesting, because most of the morphological traits were easily visible for determining diversity. For accessions with different maturity periods, data collection was done through monitoring of growth and physiological maturity of different sorghum accessions, over the growing period. Sorghum diversity within each field was measured based on morphological characteristics, such as seed size and colour, plant height and other characteristics, as outlined in the Sorghum Descriptor Guide (IBPGR and ICRISAT, 1984). In addition, two quadrats, measuring 5 m by 5 m, were used and the number of sorghum accessions in each quadrat counted. In the field, the accessions were also categorised based on the maturity periods.

For each trait assessed, two diversity indices, namely the Simpson D (Simpson, 1949) and the Shannon-Weaver H (Shannon and Weaver, 1949) were calculated to quantify the diversity in each field. Simpson diversity index is a dominance index, which gives more attention to the dominant species, and hence less dominant species are left out. On the other hand, the Shannon-Weaver diversity index is an information statistic index, which accounts for both abundance and evenness of the species. Therefore, in order to address the gaps in each of the indices, both indices were used concurrently. The diversity indices calculated at field level were subsequently aggregated at village, sub-county and district levels.

The locations of the different fields were recorded using Global Positioning System (GPS) navigator software, installed on a smartphone (Djuknic and Richton, 2001). The GPS coordinates were recorded from the centre of each field in the Universal Transverse Mercator coordinate system (UTM) format. The diversity indices were computed as follows (Meng *et al.*, 1998):

Shannon-Weaver index (H)

$$= -\sum_{i=1}^{s} Pi * In(Pi)$$

Simpson index (D) = $\frac{1}{\sum_{i=1}^{S} Pi^2}$

Where:

Pi is the proportion (n/N) of individuals of one particular variety found (n) divided by the total number of varieties found (N). *ln* is the natural log and *s* is the number of varieties.

Geographical and genetic distances between fields. The geographical distances between the fields, were calculated using the package Geosphere in R statistical software (Hijmans *et al.*, 2017). The function, "distVincentyEllipsoid", which measures the shortest distance between two points, according to the 'Vincenty (ellipsoid)' method (Vincenty, 1975) was used. Distance based on genetic diversity parameters was calculated using Gower's distances (Gower, 1971) implemented in function "daisy" in package "cluster" in R statistical software (Martin *et al.*, 2015).

Genetic distance was calculated using Gower's distance because of its ability to combine qualitative and quantitative variables. Twenty eight variables, including number of varieties in the field, diversity indices, presence/absence sorghum accessions with different colours, among others were used in Gower's distance calculation.

Data analysis. Both descriptive and inferential statistical analytical tools were used in the study. Summary statistics (means, variances and bar graphs) were used to compare diversity measures (diversity indices and number of accessions) between fields, sub-counties and districts. Analysis of variance was also performed on diversity indices and number of accessions using GenStat 12th Edition statistical package; and significant means were separated using Least Significant Difference (LSD) at the 0.05 probability level.

RESULTS

Abundance and distribution of accessions. One hundred and ten sorghum accessions were identified across the three districts based on colour, shape grain size and plant height (Fig. 1). These accessions fell into the Guinea, Bicolor, Caudatum, Kafir and Durra races. Among the sorghum accessions recorded on, released varieties included *SESO3*, *Epuripur*, *Serena, Sekedo* and "*Shila*". There was variability ($P<0.001$) in the types of sorghum (accessions) grown by farmers both within and between the three districts.

Several accessions were shared between the three districts, with 20 accessions appearing in all the three districts (Fig. 1).

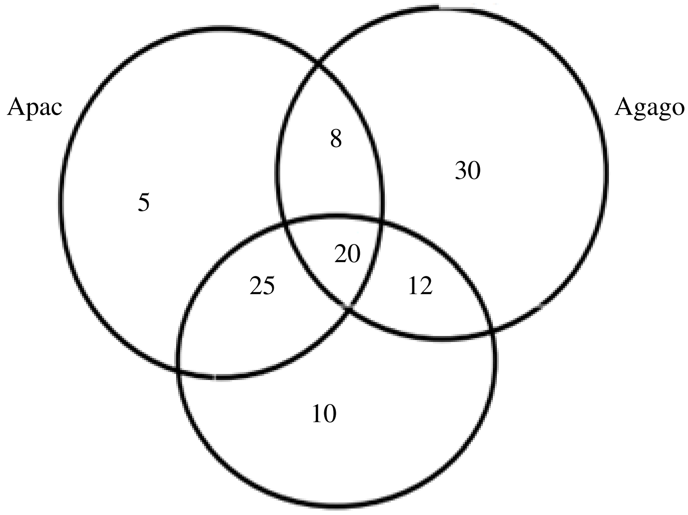

Figure 1. Abundance and distribution of sorghum accessions in Apac, Agago and Serere districts in Uganda.

Apac and Serere districts had the highest number of accessions (45) in common; whereas the least number of accessions (28) was shared between Agago and Apac. Agago had the highest number of unique accessions (30); followed by Serere (10) and Apac (5) (Fig. 1).

Sorghum accessions grown. The number of accessions grown per field varied significantly (P<0.001) among the districts, with Agago having the highest number (4.47), followed by Serere (3.93) and Apac (1.69) (Table 1). In terms of colour, the commonest types of sorghum grown in Serere were red (51.23%) and brown (47.29%) seeded types; whereas Agago had brown (62.12%), white (18.8%) and red (14.02%) types. The white type ofsorghum was dominant (56.84%) in Apac,followed by brown (32.63%) (Table 2).

Diversity indices. Shannon-Weaver diversity index varied significantly (P<0.001) among the three districts (Table 3). However, within districts, there were no significant differences for the different fields (P=0.714). Agago had the highest index (1.019), followed by Serere (0.858) and Apac (0.227).

The Simpson diversity index for Apac district ranged from 1 to 3.369, for Agago 1 to 4.762, and for Serere 1 to 5.910 (Table 4). On average, Agago district had the highest Simpson diversity index (2.440), followed by Serere (2.229) and Apac (1.285).

The Shannon-Weaver diversity index for Apac ranged from 0.000 to 1.330, for Agago 0.000 to 1.734 and for Serere 0.000 to 1.998. Overall, Agago had the highest Shannon-Weaver diversity index (1.019), followed by Serere (0.858) and Apac (0.227).

Spatial distribution. Distances between fields in different districts and Gower's genetic distance are summarised in Tables 5 and 6, respectively. The shortest distance between fields recorded was in Serere district (5.17 m) whereas the longest distance was recorded in Apac district (70,100 m).

Within each of the three districts, there was significant (P<0.05) positive correlation between geographical distance and distances based on diversity parameters (Table 7). Fields that were close to one another grew similar varieties of sorghum, but with increase in distance, both the accessions and the diversity varied. Correlations were slightly higher in

TABLE 1. Number of sorghum accessions grown by farmers in three districts of northern and eastern Uganda

	Apac	Agago	Serere
Mean	1.60	4.47	3.93
Minimum	1.00	1.00	1.00
Maximum	5.00	9.00	10.00
Range	4.00	8.00	9.00
Variance	1.09	2.49	3.28
Coefficient of variation	65.30	35.33	46.07
LSD district	0.567	0.567	0.567
LSD field	2.534	2.534	2.534

TABLE 2. Percent distribution of sorghum accessions based on grain colour in three districts in Northern and Eastern Uganda

District	Grain colour					
	Red	Brown	White	Yellow	Purplish brown	Cream
Apac	8.42	32.63	56.84	2.11	0.00	0.00
Apac	8.42	32.63	56.84	2.11	0.00	0.00
Agago	14.02	62.12	18.18	1.89	2.27	1.52
Serere	51.23	47.29	1.48	0.00	0.00	0.00

TABLE 3. The Shannon-Weaver diversity index (H) for three districts in northern and eastern Uganda

	Apac	Agago	Serere
Mean	0.227	1.019	0.858
Minimum	0.000	0.000	0.000
Maximum	1.330	1.734	1.998
Range	1.330	1.734	1.998
Variance	0.138	0.138	0.247
Coefficient of variation	163.800	36.440	57.930
LSD district	0.1542	0.1542	0.1542
LSD field	0.6895	0.6895	0.6895

TABLE 4. The Simpson Diversity index for sorghum accessions in the study districts in northern and eastern Uganda

	Apac	Agago	Serere
Mean	1.285	2.440	2.229
Minimum	1.000	1.000	1.000
Maximum	3.369	4.762	5.910
Range	2.369	3.762	4.910
Coefficient of variation	40.510	33.690	50.380
LSD district	0.3193	0.3193	0.3193
LSD field	1.4279	1.4279	1.4279

Apac and Agago districts = northern Uganda, Serere district = eastern Uganda

TABLE 5. Distances between farmers' fields in the study districts in northern and eastern Uganda

District	Number of fields	Mean distances between fields (meters)			
		Minimum	Mean	Median	Maximum
Agago	60	29.24	6,836.00	6,586.00	13,930.00
Apac	60	33.17	13,900.00	4,116.00	70,100.00
Serere	52	05.17	6,512.00	6,474.00	17,070.00

TABLE 6. Gower's distances between farmers' fields in three districts northern and eastern Uganda

District	Number of fields	Minimum	Mean	Median	Maximum
Agago	60	0.000	0.1928	0.1890	0.5277
Apac	60	0.000	0.2010	0.2143	0.4895
Serere	52	0.000	0.2046	0.1969	0.5357

TABLE 7. Correlation between geographical distance and distances based on diversity measures for sorghum varieties in farmer fields the study districts in Uganda

District	Correlation coefficient	P-value
Agago	0.138	5.24×10^{-8}
Apac	0.124	1.69×10^{-7}
Serere	0.081	3.00×10^{-3}

Apac and Agago districts than in Serere district (Table 7).

DISCUSSION

Abundance and distribution. Overall, 110 accessions from five sorghum races (Caudatum, Durra, Kafir, Bicolor and Guinea) and other intermediate races were identified across the three districts of Agago, Apac and Serere (Fig. 1).

The present findings add to the list of races recorded previously (House, 1996, cited by Olupot, 2011). Olupot (2011) reported the presence of Caudatum and Guinea races in Uganda, but not Kafir, Bicolor and Dura. There are many possible reasons to explain the absence of some races in the previous studies:

(i) It is likely that the races that were not recorded earlier, entered the country later through seed exchanges with neighbouring countries such as South Sudan, where sorghum was first domesticated;

(ii) Some of these landraces were introduced into the country later through movement of refugees, and distribution of seed to internally displaced persons by nongovernmental organisations during the 20 year war by the Lord's Resistance Army Rebels, most especially in Northern and Eastern Uganda; and

(iii) Other landraces could have been introduced into the country through the breeding process, whereby the germplasm is introduced from international partners such as ICRISAT or through cross border trade with other countries such as South Sudan which is the country of origin of sorghum.

Occurrence of accessions from all the common sorghum races in the fields is an indication of the existence of sorghum diversity on farmers' fields across the study areas.

The findings also show that farmers play a role in keeping different accessions in their fields. The red type of sorghum was more dominant in Serere district because it is early maturing and is popular in the market. However, in all the study areas, sorghum types occurred in different proportions because according to farmers, each type served a different role. For example in Agago, the white type was good for porridge; brown and red types for bead; whereas the yellow type was boiled when still fresh. Most farmers grew a particular type of sorghum for commercial purposes. For example, the white type of sorghum was more dominant in Chegere sub-county in Apac because of the high market demand by Nile Breweries Limited, a major beer company in Uganda.

The existence of diverse sorghum accessions on-farm, therefore, provides a wide range of genotypes for selection of desirable parents for breeding for high yields, drought tolerance, and pests and disease resistance; systematic collections, and characterisation.

Comprehensive knowledge of sorghum diversity is a pre-requisite for sustainability of sorghum production, most especially for adapting to climate change effects such as erratic rainfall, prolonged dry spells and increase in temperature (Sinha and Kumaravadivel, 2016).

The existence of similar accessions in more than one district (Fig. 1) could be attributed to seed exchange between farmers in different areas (Barnaud *et al*., 2007). Serere district had the biggest number of accessions in common with Apac and Agago districts, perhaps because the former is located near the National Semi-Arid Resources Research Institute where most of the sorghum breeding is carried out in Uganda. Therefore, there is a possibility that through multi-locational testing of sorghum before release, farmers in different locations gained access to different sorghum types. Relatedly, government and other non-government organisations such as Operation Wealth Creation (OWC), National

Agricultural Advisory Services (NAADS), and Northern Uganda Social Action Fund (NUSAF), distribute seed of sorghum to farmers, hence contributing to the changes in the diversity of sorghum on farmers' fields.

Food and Agriculture Organization (FAO) is one of the non-governmental organisations that supplies seeds of various crops to farmers, including sorghum, hence affecting the diversity of sorghum. Farmers often exchange seeds of landraces and improved varieties with other farmers from within their communities or involving other areas through which they gain access to new genotypes, which are adapted to similar environments (Barnaud *et al.*, 2007; Dossou-Aminon *et al.*, 2014). Barnaud *et al.* (2007) further pointed out that seed exchange, pollen flow, farmers' practices and environmental pressures affect genetic diversity *in situ*.

We found different levels of diversity of sorghum on farmers' fields, which points to the crucial role smallholder farmers play in conservation of diversity. The existing diversity offers a wide range of genotypes with various attributes that breeders can use to develop superior varieties with farmer-preferred attributes such as resistance to *striga*, pests and diseases, high yield and good quality in terms of flour, marketability.
In order to guard against complete loss of the existing diversity on-farm through agents of genetic erosion like market pressure and introduction of improved varieties, outbreak of pests and diseases, drought and floods, there is a need for germplasm collections that will be kept at the gene bank; or establishment of community seedbanks to prevent complete loss of diversity.

Accessions and diversity indices. The differences in number of accessions and diversity indices revealed different levels of diversity in the three districts (Tables 1, 3 and 4). The lack of significant differences in the number of accessions and diversity indices within each of the districts was indicative that almost the same types of sorghum were grown in different villages at varying proportions. This was observed based on the variability in the proportion in which similar accessions were grown as indicated by diversity indices. The high levels of sorghum diversity in Agago district can be attributed to farmers' uses to which different sorghum accessions were put, for example, yellow sorghum was used for boiling its panicles; white for porridge; brown and red seeded for bread, porridge and brewing. Farmers also tended to grow many accessions together to guard against total crop failure due to pests and disease outbreak; a fact that allows for extensive gene flow resulting into new crosses, which in turn contribute to diversity.

Apac district had the fewest accessions per field and most farmers grew a particular type of sorghum (*Shila*) for commercial purposes. This signifies the negative impact that promotion of improved crop varieties impose on the genetic diversity of accessions. However, some fields in Ibuje and parts of Chegere sub-counties in Apac district had more than one variety grown per field, reportedly for food security. Therefore, the difference in number of accessions in the two sub counties is responsible for the higher coefficient of variation in Apac district than Agago and Serere(Table 3).

Agago and Serere districts had, on average, four accessions per field and each of the accessions was grown for a specific use. In this case, red seeded sorghum was grown for commercial and food purposes. On-farm management of sorghum diversity, therefore, means that smallholder farmers select and develop the varieties they need to suit their end user requirements, culture, market demand and environmental pressures (Labeyrie *et al.*, 2014). In order to guard against diversity loss through genetic erosion, there is a need to establish community seed banks (CSB) or local gene banks in order to improve local access to quality seed of local landraces and other varieties of sorghum. Introduction of quality seed of traditional sorghum varieties through government programmes like Operation Wealth Creation and research institutions like National Agricultural Research Organisation, can help to maintain genetic diversity and reduce risks of genetic erosion.

Spatial distribution. The significant positive correlation between geographical distance and distances based on diversity parameters (Table 7) indicates that locations that were far apart geographically are also far apart in terms of diversity characteristics. The longest distance was in Apac district because the sorghum fields in Ibuje sub-county were far apart from each other and the distance from the last field sampled in Ibuje to next field in Chegere sub-county.

The farmers' practices such as seed exchanges, marketing and values they attach to different sorghum types contributed to spatial distribution of sorghum accessions. For example, farmers whose fields were close to one another had closely similar accessions of sorghum grown in their fields compared to those that were far apart.

Farmers tend to cultivate a variety of accessions depending on the different values they attach to them; for example in Serere district, most of the farmers cultivated the red type of sorghum because of good attributes that they attached to them such as early maturity, drought tolerance, high yield, good brewing and bread qualities, and this could be responsible for the weak correlations. On the other hand, to meet farmers' dietary and other needs, fields that were intercropped with other crops such as sesame, finger millet tended to have more than one sorghum accession. This could be one of the reasons why the magnitude of correlation coefficient between distance and diversity was slightly higher in Apac because in some areas like Chegere, farmers cultivated one type of sorghum. Elsewhere, little evidence for spatial genetic structure (for example; variation among fields for a given landrace) was reported in Duupa sorghum populations (Barnaud *et al*., 2007).

In general, the findings of this study indicate that sorghum fields that are close to one another are relatively similar in terms of diversity because of extensive gene flow among different accessions sown together. Therefore, depending on the prevailing conditions for example in case of an outbreak of pests, or diseases that affect the yield, farmers can decide to conserve or lose diversity together which has both positive and negative implications.

CONCLUSION

This study has shown that different levels of diversity of sorghum accessions exist on farmers' fields in Northern and Eastern Uganda; with the highest levels in Agago district and lowest in Apac district. In Agago, the most dominant types of sorghum are the brown, red and white seeded ones, which are all late maturing. In Serere, the dominant type of sorghum is the red short early maturing genotype and the reason for their dominance was ready market, good flour for bread and porridge. On the other, white seeded type of sorghum dominated in Apac district with most fields having only one type of accession.

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