Global Strategy for the conservation and use of genetic resources for sorghum (Sorghum bicolor (L.) Moench)

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Executive Summary

Sorghum [*Sorghum bicolor* (L.) Moench] is a widely adapted cereal crop that can be grown in a wide diversity of ecologies in the semi-arid, sub-tropical, tropical, and temperate climates. Sorghum is the fifth most important grain crop internationally. It is mainly grown on marginal, rainfed land that are subject to periodic droughts. In some other areas of the world, such as the United States, Mexico, Argentina, Brazil, Australia, China, and Japan, it is an important feed crop with a significant value from trade. The areas of production for sorghum have declined in most regions of the world except Africa, where it is an important for

household food security and as a contributor to poverty alleviation, but it also has significant cultural value. The shifts in the importance of the crop for production, utilization and trade are a risk for loss of conserved genetic resources in ex situ collections in countries where sorghum is seeing a decline in investment into research and development. In the tropics, the production of sorghum has increased with a shift to more marginal areas where is an important food and feed security crop in environments challenged significantly by climate change. The challenges of climate change in the traditional production areas risk genetic erosion in farmer's fields and natural areas for the crop wild relatives. It is also a challenge for farmers to adapt given the poor productivity of the crop in Africa and the lack of investment into sorghum research and development in these areas also. Thus, the production of sorghum globally is vulnerable, and it is facing many constraints that will depend on the use of the genetic diversity that is conserved for the future.

The cultivated crop, *Sorghum bicolor* subsp. *bicolor* has significant genetic diversity but there are also many related species that have unique traits and adaptation that could serve as a source of improvement in the future. The diversity within landraces is extensive and is a product of differences in genotypes, environments, and social systems. The use of genetic resources in the improvement of sorghum production has been important in the past and the breeders of the crop continue to put high priority on improving traits related to changes in the climate of the target environments, such as drought tolerance, cold or heat tolerance, pest/disease resistance, or the need for shorter duration varieties. This need has resulted in an increased use of genetic resources such as elite lines from other breeding or research programs, landraces sourced from local farmers, and wild relatives. This increased interest of the users of genetic resources presents both future opportunities for *ex situ* collection holders but also challenges to meet the needs of the end users.

Global conservation strategies facilitate a transition from the current complex, fragmented, and independent crop conservation system to a more integrated, collaborative, and cooperative global conservation system. The objective of the update for the 2007 global strategy for sorghum was to consider changes in the global system in terms of the security of conservation and enhanced use of ex situ collections. This re-assessment is used to identify priority global actions to address vulnerabilities and enhance global collaboration. The update utilized a background study, a survey of 37 institutions on the status of conservation and use of their collections, an analysis of the current accession level composition of sorghum collections, and a consultation with users.

Overall, the survey respondents conserved about 80% of the global accessions. Landraces are the predominant type of accession being conserved but there are few accessions of the wild species conserved ex situ. Globally, there is evidence of significant redundancies in the composition of ex situ collections that is a product of the history of donation, acquisition, and joint collections, for example, there are twenty institutions that conserve 72% of the global accessions that mainly derive from 11 countries. In the 2007 Strategy, there was a recognition that the high degree of duplication made it complicated to interpret the adequacy of the diversity and coverage of the accessions conserved globally. There are significant gaps remaining in West and Central Africa as well as South Sudan that were identified in 2007. The assessment of the consolidated database for Central America, Central Asia, and the Caucasus indicate there are potential gaps in terms of secure conservation as well as the need for collection. Finally, the species coverage is still seen as inadequate as well as ecological sampling at the national level. As we gain a much greater understanding of genotypic or allelic diversity through enhanced genomic tools and the application of estimates of social and cultural diversity, it is feasible to utilize a global approach to the identification of duplications and gaps that will build upon greater collaboration and information sharing to address a global need for a more rational, cost-effective conservation and use system for sorghum genetic resources.

Generally, there are genebanks that conserve more global collections that meet the internationally recommended standards for conservation of orthodox seed to a greater degree than the national collections. Many national genebanks in the centers of diversity had limitations related to inadequate facilities, equipment, staffing, regeneration sites, and resources. This is leading to backlogs in viability testing, backlog, regenerations, and multiplication that is a risk for long term conservation and has limited the quantity and quality of seed available for distribution. There are also constraints in routine operations to ensure the use of the most efficient and secure procedures and protocols through SOP's, QMS, and research. Finally, there is an increased awareness of the need for safety duplication and many institutions are committed to secure the collection with a back-up, but it is not a priority given the significant constraints. This is a vulnerability for the global system that needs to continue to be addressed.

Priority needs have been identified in term of gaps in routine operations, facilities, equipment, and procedures where there are backlogs or a significant need for upgrades. Many of these are due to the reliance of the genebanks on short term specific project funds that are not certain and seem to be declining. The financial support for long term conservation and use is not a priority for many donors and the relatively lower priority that is given internationally and nationally for sorghum has resulted in few opportunities for funds to address these gaps. The lack of global action to address these collection specific constraints is a risk for the conservation of a high proportion of the unique diversity.

In summary, the current global system consists of two types of ex situ collection holders, many farmers in Africa and South Asia, and in natural areas. It is a fragmented, insecure system that is vulnerable to genetic erosion due to changes in the climate of the more marginal semi-arid tropics, the low priority given to the crop in many countries and by the private sector, and the lack of links to users. The 2007 strategy recommended several actions to address the constraints in conservation and use but there were very limited outcomes for these. The two global actions identified in this update of the global strategy in 2021 are built upon those recognized earlier with the additional insight of a broader range of institutes that conserve sorghum genetic resources and key users. There is a recognition that the future need for collections needs to be considered now and actions need to be taken.

Introduction

The Crop Trust is an international organization working to safeguard crop diversity for the very long term by focusing on ex situ conservation in genebanks. Since 2006 it has worked with crop conservation and hired specialists to develop global *ex situ* conservation strategies for key global food crops and commodities. Global conservation strategies facilitate a transition from the current complex, fragmented, and independent crop conservation system to a more integrated, collaborative, and cooperative global conservation system. The aim of a global strategy for sorghum is to provide the evidence for priority strategic action.

In 2007, the Strategy for the Global Conservation of Sorghum Genetic Diversity was completed. The development of the strategy involved a survey of the key *ex situ* collection holders on the status of conservation and use to assess the state of global conservation. This summary was followed up with a workshop with experts to discuss the various conclusions of the survey, make key recommendations, and initiate global actions to address priorities. The primary goal of the strategy was to facilitate the development of an efficient and effective conservation system for sorghum genetic resources that was referred to as an "International Sorghum Germplasm Collection". This included:

- Assessment of the composition, conservation standards, and role of global, regional, and national collection holders
- Identification of key gaps in existing world collections
- Establish model for collaboration to share responsibilities and cost for the management of conservation by the key genetic resource collections
- Identification of the key information needs for comprehensive global database network to enhance conservation, exchange, and utilization

- Identify capacity building needs to upgrade and enhance the various collections

The results from the survey of collection holders were discussed at a consultation workshop held with key experts in conservation and use. The workshop identified key recommended actions that would be implemented by five task forces that was oversighted by a Global Sorghum Group that needed to be taken to secure conservation and use for the long term in a global system. The workshop concluded that the strategy should be published, and efforts made to implement it. They recognized that the global strategy was not static and needed regular review with revision as needed. Some of the key issues identified were:

- There are several constraints to secure and effective conservation such as limited safety duplication, a need for urgent regeneration, and poor storage infrastructure.
- In general, there was limited availability and sharing of accession-level information with users.
- There was limited availability of accession to users, except for a few collections such as ICRISAT and USDA-ARS.
- Only a fraction of sorghum crops accessions conserved in genebanks were used in crop improvement programs (for example, in temperate environments predominantly photoperiod insensitive materials are screened)
- There was a lack of effective links of conservation to users due to poor information flow between genebanks and users, poor level of engagement between genebanks and crop-based research institutes, and poor links of genebanks with *in situ*/on farm conservation efforts.

The 2007 Strategy identified three key areas for global collaboration which included the development of a global accession level information system, a joint evaluation program, and an urgent regeneration program. Annex 5 identified five task forces with a set of tasks established and in three of the five task areas there has been some progress. There was a revision of the sorghum descriptors and a revision of the classification of sorghum that have been published. Currently, there is global sharing of passport information on accessions through Genesys where 56 institutions now share information on 118,152 accessions. A Crop Trust project focused on urgent regeneration that resulted in 7,272 accessions being regenerated and more securely conserved globally. There was also a publication of a regeneration guideline for sorghum. The success of these global collaborations indicates the importance of the Strategy to facilitate the identification of priority needs for securing long-term conservation and use of sorghum genetic resources.

The update to the global conservation and use strategy for sorghum genetic resources is the outcome of a background study of the crop importance, its genetic diversity, the use of the germplasm, an assessment of various databases with accession level information on collections, a survey of major sorghum collection holders, and a consultation with experts on the future of conservation and utilization. The focus of the 2021 survey was on the composition of the accessions conserved in *ex situ* collections and the status of *ex situ* collections in terms of the security, effectiveness, and sustainability of conservation. The survey addressed the interrelationship between individual collections in the global system, based upon collection history, collection composition, and specific activities linking conservers. There have been follow-up consultations with genebanks curators and users in the development of this update and this added effort will ensure commitment to a global system by which sorghum crop conservation and use efforts could become more secure, coordinated, systematic, and efficient. A key outcome of this effort will be the identification of priority actions to address short falls in the current global conservation system. These will be used by the Crop Trust and others to identify key investments needed to secure conservation and use for long term.

Economic Importance

Sorghum [*Sorghum bicolor* (L.) Moench] is a widely adapted cereal crop that can be grown in a wide diversity of ecologies in the semi-arid, sub-tropical, tropical, and temperate climates. Sorghum is the fifth most important grain crop internationally. It is mainly grown on marginal, rainfed land that are subject to periodic droughts with its extensive root system and its ability to become dormant during water stress. It also some degree of tolerance to high temperatures and salinity (Bhagvatula et al, 2013; OECD 2016).

While the crop is grown in the much of the world for a feed and fodder crop, it is also a staple food for millions of people in the semi-arid regions of Africa and south Asia. Batey (2017) identified four major groups of sorghum: grain, sweet, forage, and broom. Batey (2017) also reported that the utilization of the different types varied considerably in the various regions of the world. In the Americas, Europe, and Australia, 94-100% of the production is used for feed and only about 0.4% is used for any other use such as ethanol production. In African and Asia, 73-79% of the production is used as a food crop in household products such as porridge, bread, cake, couscous, and other dishes (Reddy et al, 2008). In Africa is also used to traditionally produce local beer (Sawadogo-Lingani et al., 2021) while is Asia is an important feed for livestock and poultry. In the more temperate regions of the world, it is used mainly for feed and as a feedstock for ethanol production. It is also an important forages and sweet sorghums are used as sweeteners or fermented into ethanol. The plant and stover have other important uses in Africa and Asia.

Sorghum is grown in five main regions of the world, Africa, Americas, Asia, Australia, and Europe. The top ten countries listed in Table 1 for 2020/21 accounted for about 75% of the global production and consumption from 2017 to 2021 (FAS/USDA 2021). The top seventeen producing and consuming countries for 2020/21 accounted for 89% of the total global production and 83% of the consumption. There were three countries, United States, Argentina, and Australia, who consume domestically less than half of their production. So, while some countries did not meet their domestic consumption entirely through production, China is the only country that consumed more than three times its domestic production. So, while the United States is the largest producer of sorghum globally, China is the largest consumer. In fact, China imported more than 80% of the sorghum imported globally. Most countries rely mostly on their own production.

Table 1. Production (Thousand Metric Tons) and Consumption (Thousand Metric Tons) for sorghum in 2020/21 (Foreign Agricultural Service/United States Department of Agriculture 2021).

	Production (thousand metric tons)	Consumption (thousand metric tons)
USA	9474	2667
Nigeria	6570	6550
Ethiopia	5200	5300
Sudan	5000	4850
India	4780	4550
Mexico	4000	4100
China	3550	11600
Argentina	3400	1800
Brazil	2732	2700
Niger	1922	2000
Mali	1801	1700
Burkina Faso	1560	1700
Australia	1350	300
Cameroon	1200	1225
Bolivia	1100	1050
European Union	1003	1013
Chad	980	1000
Others	7618	7842
World Total	62237	62374

Sorghum production and productivity have changed over time. Figures 1a, b and c highlight this for area of production (thousand ha), production (thousand metric tons), and productivity (tons/ha) for three 20-year phases from 1961 to 2019. Generally, the area under production and the total production has more than doubled in Africa but the productivity per ha has only increased slightly. In Asia, the area under production and production has declined by more than 50% and productivity has increased at a slightly higher rate than in Africa. In these regions, production is mainly done by smallholder farmers with very limited use of inputs.

Figure 1a. Area of production (thousand ha) for sorghum in Africa, Asia, Americas, Australia, and Europe in the 1961 to 1980, 1981 to 2000, and 2001 to 2019. (source FAO 2021)

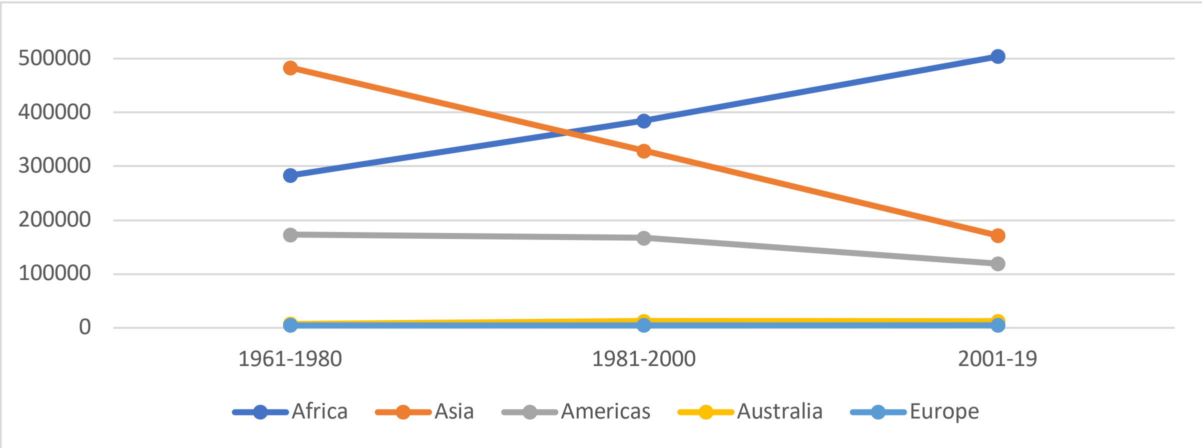


Figure 1b. Production (thousand metric tons) for sorghum in Africa, Asia, Americas, Australia, and Europe in the 1961 to 1980, 1981-2000, and 2001-2019 periods. (Source FAO 2021)

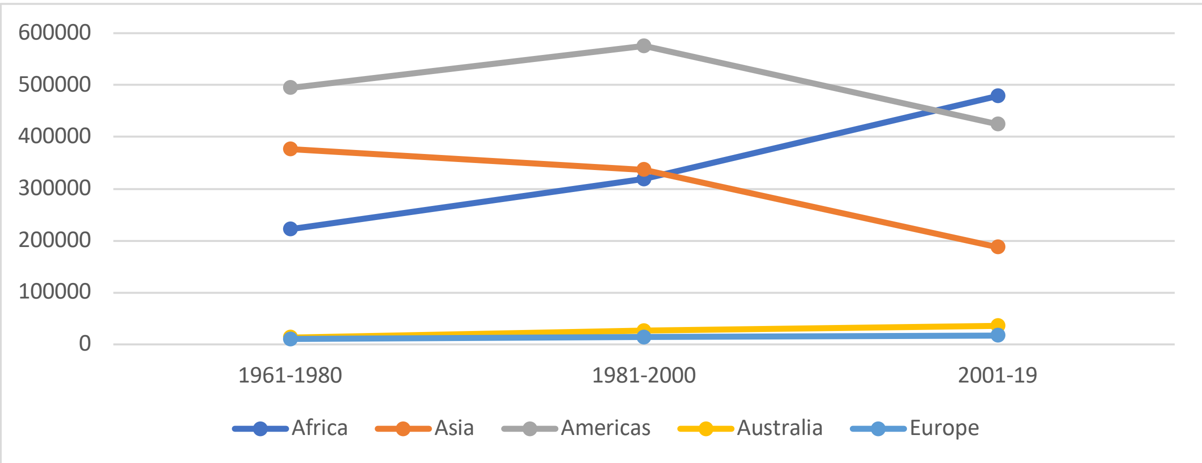
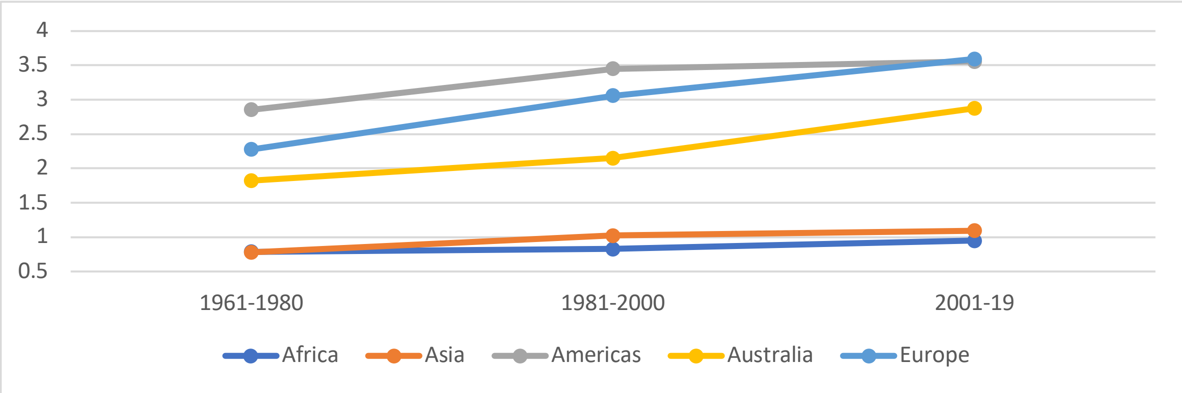


Figure 1c. Productivity (tons/ha) of sorghum in Africa, Asia, Americas, Australia, and Europe in the 1961 to 1980, 1981-2000, and 2001-2019 periods. (source FAO 2021)



The historical trends are very different for sorghum production in the Americas, Australia, and Europe where the production systems are much more intensive with much more investment into research and development for improved sorghum production. In the Americas, the area under production and the productivity increased from 1961 to 2000 but the total production continues to decline. The productivity has leveled off from the 1980 to 2019. In Australia and Europe, the productivity continues to increase, as has the area under production. Only in Australia has the production increased to a significant degree over the three periods.

Mundia et al (2019) presented an assessment of the history and current constraints as well as opportunities for sorghum production based on an extensive review of the literature to identify the primary drivers and develop insights into dynamics of the key variable in relation to global and regional production in India, China, United States, Mexico, Nigeria, and Burkina Faso. Through this assessment, ten key factors were identified that impacted on sorghum production in countries where vulnerable populations live that depend upon sorghum. These factors included climate change, agricultural inputs, population/economic growth, sorghum genetic diversity, agricultural resource scarcity, other crop demands, price, non-food demands, cultural influence and armed conflict. The ten impact of the factors and their interrelationship was compared for the six countries in the three regions and the most important factors globally were improved agricultural inputs, population/economic growth, and climate change. All the other factors, especially genetic diversity, culture, and conflict had an impact in specific localities, countries, or regions. The assessment concluded that policy intervention should be targeted to populations in at risk areas since sorghum production is most variable in areas with lower capacity to adapt to climate change. Possible interventions included facilitated seed exchanges, development of new varieties, and crop insurance plans. Monitoring sorghum production in these localities could be used as an indicator for the need to address malnutrition and famine with the crop fails.

Hyman *et al.* (2016) considered the role of sorghum, among other cereals, in 18 farming systems where dryland cereal and legumes were produced on significant area and where more than 60% of the poor live globally. Sorghum made up more than 20% of the agricultural area in three farming systems in sub-Saharan Africa: (1) cereal root crop mixed where it is the dominant cereal, (2) agropastoral sorghum-millet systems, and (3) pastoral systems. Sorghum is the dominant cereal in the dry rainfed system in South Asia. The agropastoral sorghum-millet system, the pastoral system, and the dry rainfed system are all characterized by extensive production over large areas with low productivity per unit land area. Sorghum is the dominant crop in four of the eight farming system with the poorest people. They determined the productivity (yield) of sorghum as well as other dryland cereals such as pearl millet and small millets and found the yield for sorghum was equal or lower than that of the millets in the farming system in sub-Saharan Africa and South Asia. The farming system where sorghum dominates is characterized by a high drought and high temperature stress as well as soil acidity, low soil nutrient availability, and low water holding capacity. Hyman *et al*. (2016) concluded that sorghum is the main dryland cereal in the dominant farming systems where poor people live in poverty with low nutritional status. These cropping systems have significant abiotic stress and are being impacted by climate change with increased temperatures and prevalence of drought. There were farming systems which would benefit from greater research and development investment to improve the production and nutrition of sorghum as well as the increased market development for the crop.

Orr *et al*. (2020) reported on a synthesis of unpublished literature from ICRISAT that included studies on adoption of varieties, crop production practices, and processing technologies as well as value chain development and impacts. The study modeled four scenarios, a “baseline” model set income and population growth as medium with no impact of climate change; an “optimistic” model with low population growth, high income growth and no clime change impact; an “increased productivity” model where yield growth rate for sorghum increased 25% above the baseline; and a “climate change” model that included both increased temperature and decreased rainfall. Using these models, Orr *et al.* (2020) assessed the investment potential for research and development as well as commercialization for East and Southern Africa. The business case for investment into research and development was clear with a projected growing demand for sorghum driven by high population growth and increased production that was projected to triple by 2050. This increased production would reduce poverty and increase household food security based upon where sorghum is grown, the higher yields, and the shortened hungry periods since most of the varieties adopted are of shorter duration as compared with the traditional varieties. They are also more resilient to climate change so the return to investment in research and development would be high. This was not the situation projected for commercialization where there is evidence for a “subsistence production trap” for many of the sorghum specific value chains. Sorghum has a higher price than maize so that limits substitution for livestock feed and the flour value chain, to address this the yield for sorghum would need to increase with a drop in price. This may be seen in some specific smaller value chains, such as clear beer, but it will not impact the more significant value chains. Generally, they concluded that commercialization will not drive adoption of new varieties or improved production practice so the business case for investment is lower.

Zereyesus and Dalton (2017) also found high social rates of return from investments into sorghum research and development with higher productivity and consumer benefits to individuals in the semi-arid and arid regions of the world. They reported on a meta-analysis of 59 studies the were done between 1958 to 2015 and reported rate of estimated return. They concluded that the return on sorghum research and development ranged from 58-81 %/year and was socially profitable since the source of research funds were from public-supported investment. The higher rates of return were seen when the impact was quantified for more local areas rather than at the national or international level. Technological innovation had greater returns when it focused on narrow adaptation to specific agroecological conditions. The highest rates of return were found in the United States where the economic environment and cost for research was more favorable.

Bhagavatula *et al*. (2013) reported that sorghum production in Asia had declined steadily from 1980 to 2009 at about 3% per year. The greatest decline was in India and China. In the rainy season sorghum area of India, the area of production declined 4.5% per year while post-rainy season sorghum area only declined by about 1% per year. This is a production area where other crops are not competitive when grown under residual moisture and the stover is a high value product as well during the dry season. Their study concluded that the importance of sorghum as a food staple had been declining from the 1980’s until 2009/10 in all the other agroecologies in India but it is now slowly starting to increase mainly due to its alternative use as a feed grain, in alcohol, and in processed food. More than 50% of the crop is used for these alternative but productivity is still low, especially in rainfed conditions where there is a need for greater yield stability with greater pest and disease resistance. There is also a need to develop varieties with improved traits for these alternative uses as well as to focus on other the grain and stover as important products.

So generally, sorghum is an important cereal for international trade as well as domestic consumption nationally. It is an important crop for reducing poverty and increasing household food security in sub-Saharan Africa and South Asia. It is also a very important cereal crop in the agroecologies where farmers still depend upon the local varieties which conserve significant genetic diversity of the crop. Thus, investments into conservation and use of genetic resources is critical to ensure the improvement in the crop productivity and adaptation to these increasingly marginal agroecologies.

Crop Evolution

Sorghum is a domesticated crop that is taxonomically classified in the kingdom Plantae, division Magnoliophyta, class Liliopsida, order Cyperales, family Poaceae, tribe Andropogoneae, subtribe Sorghinae, and genus *Sorghum*. Ananda *et al.* (2020) presents and extensive review of the history and status of classification in the *Sorghum* genus. There are several different views of the number of species and their classification into sections but according to the USDA (2021), there are 25 accepted species with three subspecies for the cultivated *Sorghum bicolor* and these are listed in Table 2. There are five sections within the Sorghum genus but only those species within the Eu-sorghum section are within the primary and secondary genepool for the domesticated crop. Within the secondary genepool, Sorghum x *almum* is a hybrid between *S. halapense* and *S. bicolor*. Most of the species within the tertiary genepool are found only in Australia and only two species, S. purpureosericeum and S. versicolor are distributed in Africa.

Table 2. Species within the Sorghum genus in the five sections, classified into the genepool for cultivated sorghum and their distribution.

Species	**Section**	**Genepool**	**Distribution**
Sorghum bicolor (L.) Moench subsp. *bicolor*	Eu-sorghum	primary	Africa
Sorghum bicolor (L.) Moench nothosubsp. *drummondii* (Steud.) de Wet ex Davidse	Eu-sorghum	primary	Africa
Sorghum bicolor (L.) Moench subsp. *verticilliflorum* (Steud.) de Wet ex Wiersema & J. Dahlb.	Eu-sorghum	primary	Africa
Sorghum propinquum (Kunth) Hitchc.	Eu-sorghum	primary	Southeast Asia and Indian subcontinent
Sorghum halepense (L.) Pers.	Eu-sorghum	secondary	Southern Eurasia and India
Sorghum × *almum* Parodi	Eu-sorghum	secondary	Southeast Asia and Indian subcontinent
Sorghum purpureosericeum (Hochst. ex A. Rich.) Schweinf. & Asch.	Parasorghum	tertiary	India, Sahel, east, and west tropical Africa
Sorghum versicolor Andersson	Parasorghum	tertiary	East and Southern Africa
Sorghum grande Lazarides	Parasorghum	tertiary	Australia
Sorghum leiocladum (Hack.) C. E. Hubb.	Parasorghum	tertiary	Australia
Sorghum matarankense E. D. Garber & Snyder	Parasorghum	tertiary	Australia
Sorghum nitidum (Vahl) Pers.	Parasorghum	tertiary	Australia, New Guinea, Southeast

			and East Asia
Sorghum timorense (Kunth) Büse	Parasorghum	tertiary	Australia and Timor
Sorghum amplum Lazarides	Stiposorghum	tertiary	Australia
Sorghum angustum S. T. Blake	Stiposorghum	tertiary	Australia
Sorghum brachypodum Lazarides	Stiposorghum	tertiary	Australia
Sorghum bulbosum Lazarides	Stiposorghum	tertiary	Australia
Sorghum ecarinatum Lazarides	Stiposorghum	tertiary	Australia
Sorghum exstans Lazarides	Stiposorghum	tertiary	Australia
Sorghum interjectum Lazarides	Stiposorghum	tertiary	Australia
Sorghum intrans F. Muell. ex Benth.	Stiposorghum	tertiary	Australia
Sorghum plumosum (R. Br.) P. Beauv.	Stiposorghum	tertiary	Australia
Sorghum stipoideum (Ewart & Jean White) C. A. Gardner & C. E. Hubb.	Stiposorghum	tertiary	Australia
Sorghum laxiflorum F. M. Bailey	Heterosorghum	tertiary	Australia and New Guinea
Sorghum macrospermum E. D. Garber	Chaetosorghum	tertiary	Australia
Sorghum trichocladum (Rupr. ex Hack.) Kuntze		tertiary	Mexico, Guatemala, Honduras

Ananda et al (2020) reviewed the evidence for the cross compatibility of sorghum with its wild relatives in the various genepools. The three subspecies of the domesticated species, S. bicolor, are fully interfertile and they also grow sympatrically with the local varieties in the agricultural regions of Africa. There are several studies on the gene flow between the crop and the wild relatives in Kenya, Ethiopia, Niger, Cameroon, and Western Africa (Tesso et al, 2008; Sagnard et al, 2011; Mutegi et al, 2011; Mutegi et al, 2010; Mutegi et al, 2012; Barnaud et al, 2009; Fernandez et al, 2014; and Okena et al, 2012). Thus, there is a close relationship between cultivated sorghum and its progenitor, subsp *verticiliflorum* as well its weed relative in the center of origin of the crop.

Ananda et al (2020) also summarized the evidence for cross ability and transfer of traits from *S. propinuium* in the primary genepool and *S. halapense* in the secondary genepool. *S. x almum* is a natural interspecific cross between these two genepools. Ohadi et al (2017) reviewed the attempts that have been made to cross cultivated sorghum and it wild relatives, especially in the tertiary genepool. Ananda et al (2020) concluded that the species in the tertiary genepool had many traits that offered improvement in adaptation for specific ecologies. Kuhlman et al. (2010) described the use of the *iap* gene from *S. bicolor* to allow for the development of hybrids with *S. macrospermum* in the tertiary genepool.

Sorghum was domesticated in the Ethiopia-Sudan region in Northeast Africa (de Wet, 1978) from subsp *verticilliflorum.* The primary center of origin and diversity in sub-Saharan and Northeast Africa while the secondary centers are found in India and China. A single domestication event occurred in the center of domestication and the racial diversity found globally was due to a migration-dispersal. The only exception reported is the possible independent domestication of race guinea subrace margaritiferium (Due et al, 2006; Figueirredo et al, 2008) but this is still not clear.

After domestication in East Africa, sorghum dispersed across much of sub-Saharan Africa. OECD (2016) and Smith and Fredrickson (2000) presented an illustration of the origin and movement of the five races of sorghum within Africa, to the Indian sub-continent and China, and the return of race Durra to East Africa. This movement was related to migration and trade to India, China, and the Americas.

Dahlberg (2000), de Wet (1978) and Harlan and de Wet (1971) describe the four races of subsp *verticilliflorum* and their distribution in sub-Saharan Africa. These four races have been recognized an ecotypes rather than races due to the morphological and ecological similarities but they do have clear distinct geographical niches. Dahlberg and Rosenow (2018) describe the major races of sorghum and the working groups based upon spikelet/panicle morphology. The classification, origin, and distribution of the five major races are also summarized.

Crop and Landrace Diversity

Doggett (1988) hypothesized that diversity of sorghum landraces, varieties, and races is a product of migration of people, disruptive selection, geographic distance, gene flow from the wild subspecies to the cultivated varieties, and cross pollination. Westengen et al (2014) evaluated the farming-language co-dispersal hypothesis in relation to geographic patterns in sorghum genetic diversity distribution and its association with ethnolinguistic groups. They found that social and cultural factors that were described by the linguistic groups was the predominant structural factor that accounted for the pattern of diversity within Africa. All the other factors were contingent on the social and cultural factors. They also considered the origin and resilience of local genetic diversity. Westengen et al (2014) concluded that for sorghum in Africa, there was evidence of farmers-language codispersal in its crop evolution. They postulated that this an example of a successful social-ecological adaptation by the farmers to the changes in the climate that was also occurring during the past in sub-Saharan Africa since the drought tolerance of sorghum enabled the cultivators to successfully migrate to new areas.

Because of the explosion in the development of genomic resources for sorghum, global assessments of diversity and their genetic basis have been published and form a useful basis for sorghum, and other crops, to link conservation and utilization. At the “meta” level, key studies include: (1) Casa et al. (2008); Billot et al. (2013); Morris et al. (2013); Mace et al. (2013); Lasky et al. (2015); and Yu et al. (2016). These strategies and data sets now serve to elucidate levels of diversity in the species as well as provide the tools needed for discovery and genetic dissection of key agronomic and compositional traits.

In complement, over the last 20 years there have been a number of reports on the degree and distribution of phenotypic and genotypic diversity at the “micro” level among and within landrace or farmers’ varieties. These are listed in Table 3. Many of these studies considered that one of these assessment of diversity as a very important step in the development of a national collection that conserved traditional varieties *ex situ* but also enhanced their use in developing improved varieties that meet the adaptation and use for local producers and consumers. Most of these studies concluded there was a high degree of genetic diversity or variability among the local varieties. The varieties were grouped or clustered by race classification, geographic or agroecological adaptation, culinary use, or ethnicity of the farmers, or other basis. There was considerable variation between varieties within the geographical zones or in the groupings that was postulated to be a result of farmers seed exchange or some degree of cross pollination dues to farmers growing multiple varieties together in the fields. The various studies demonstrated the important of landraces to subsistence farmers who maintain and use a significant degree of diversity across a wide range of agroecologies globally.

Table 3. Reports on phenotypic and genotypic diversity among collections of local landraces that were collected in situ or conserved ex situ outside the country of origin

Reports	**Sample and locality**	**Diversity measures**
Westengen et al 2014	20 seed lots collected from granaries and fields in 2010 and 2013 from Lafon villages in the southeastern part of South Sudan as well as 1983 ex situ collection.	19 SSR markers
Adunga (2014)	20 plants per 8 landrace populations from Wello, Gibe River valley, and Metekel zone in Ethiopia	7 phenotypic traits and 12 SSR markers

Reports	Sample and locality	Diversity measures
Rabbi et al (2010)	Sample from 23 on-farm and farmer saved seed collected from two contrasting agroecologies in eastern Sudan and western Kenya	16 SSR markers
Mutegi et al (2011)	329 cultivated and 110 sorghum seed samples collected from farmers' fields in the four main sorghum production regions in Kenya and from the National Genebank of Kenya	24 SSR markers
Ngugi and Onyango (2012)	139 accessions of landraces from various sorghum growing regions in Kenya	11 SSR markers
Deu et al (2008)	484 varieties collected from 79 villages distributed across Niger	28 SSR markers
Nauora et al (2019)	56 cultivars of dry season sorghum collected at three important zones of production in Southern Chad	21 quantitative traits and 11 qualitative traits
Missihoun et al (2015)	61 accessions collected in 13 villages in four districts in North west Benin	20 SSR markers
Dossou-Aminon et al (2015)	142 accession of sorghum landraces collected from 3 departments in Northern Benin	10 qualitative and 14 quantitative traits
Girma et al (2020)	2010 accession from EBI collection that represented major sorghum production environment with different stresses, local production systems and local uses.	16 morphological traits, 6 quantitative traits, and genotyping with GBS
Amelework et al (2013)	200 landraces collected from seven lowland districts in Ethiopia	30 SSR markers
Dje et al (2004)	Two farmers field sites in Northwestern Morocco	5 SSR markers
Danqual et al (2019)	7 cultivars and 34 accession collected from Northern Ghana	22 SSR markers
Majaju and Chakauya (2008)	47 landraces collected from farmers in two districts in Zimbabwe	24 morphological traits
Mofokeng et al (2014)	103 accessions that included 69 landraces from 6 provinces and 2 breeding programs in South Africa	30 SSR markers
Labeyric et al (2014)	290 samples collected from 3 ethnic groups in a study site on the Eastern slope of Mount Kenya	22 SSR markers
Burow et al (2012)	159 landrace accession collected originally from main sorghum production area in the Northeast and other cold regions of China	41 SSR markers
Barro-Kondombo et al (2010)	124 landraces collected from 10 villages in 3 regions of Burkina Faso	28 morphological traits and 29 SSR markers
Nikiema et al (2020)	120 accessions that included 92 collected from farmers a wide range of agroecologies mainly in Central Burkina Faso	28 SSR markers
Ng'uni et al (2011)	27 landraces represent two agroecological zones in Zambia	10 SSR markers
Bucheyeki et al (2009)	40 landraces collected from South and Central Tanzania and 2 from Zambia	14 morphological traits
Tovignan et al (2015)	84 accession, mainly Senegalese landraces	22 morphological traits, including biomass and stem sugar quantification
Ghebru et al (2002)	28 accessions from Eritrea, both lowland and highland collections	15 SSR markers

Reports	Sample and locality	Diversity measures
Elongavan et al (2009)	674 accessions collected from seven state in India	Economic, culinary, and adaptation traits from farmers
Ganesmurthy et al (2010)	63 local varieties collected from Tamil Nadu, India	9 morphological traits
Zhang et al (2014)	184 accessions of Chinese landraces conserved at USDA-NPGS	SSR markers
Grenier et al (2004)	2017 accession from Sudan conserved at ICRISAT	9 quantitative and 10 qualitative traits
Maina et al (2018)	520 accessions from Niger conserved at USDA-NPGS	144,216 SNP
Faye et al (2019)	421 accessions from Senegal conserved at USDA-NPGS	213,916 SNP
Cuevas and Prom (2020)	318 accession from Sudan conserved at USDA-NPGS	183,144 SNP
Girma et al (2019)	1425 accessions from Ethiopia conserved at EBI	72,190 SNP

There were limited studies on diversity amongst local varieties that were grown within an agroecology that cut across national borders. Nikiema et al (2020) reported that the clustering and distribution of the diversity amongst the collections from farmers in Central Burkina Faso was like that reported for Niger and Mali which has a similar agroecology and thus must share some of the same varieties. A similar result was reported in Bucheyeki et al (2009) for landraces from Southern and Central Tanzania and Zambia. Thus, there is value to consider greater across border collaboration in this assessment.

It was now possible to assess the risk of loss of diversity in these localities with the many challenges for sorghum from the changing climate and other threats for the local genetic diversity. Deu et al (2010) considered the temporal dynamics of genetic diversity with an assessment of diversity among collections made in 1976 and a recollection in the exact same villages in 2003. Generally, they found no major loss of genetic diversity in the last 26 years but the study did provide evidence of the differences in the evolution of allelic richness and gene diversity due to socioeconomic factor differences across the regions. This evolution can also be dependent upon the cultural identity of the farmers. The study did conclude that these assessments of temporal changes require more data collected at the local level on the socioeconomic factors, especially information in seed exchange.

Lebeyric et al (2014) assessed genetic diversity among varieties collected from farmers in a among three ethnic groups in a single site in Eastern Kenya. They found that social boundaries associated with ethnolinguistic diversity influenced the distribution of varieties and their special distribution. This affect was only seen for the landraces and not the improved varieties. They concluded that crop diversity patterns are a product of the interaction of genotype, environment, and social boundaries, especially in subsistence farming systems where crop evolution is ongoing. The social boundaries limit seed exchange and the diffusion of plant material since they depend upon social relationships.

Leclerc and d'Eeckenbrugge (2012) described the important role of social component in crop evolution, maintenance, and use of crop diversity by individuals and society. They conclude that crop diversity organization is a result of the three-way interaction of genotype, environment, and social differentiation factors. De Wet (1978) recognized that racial evolution in cultivated sorghum was closely associated with ethnological, ecological, and geographic isolation that have resulted morphological differentiation that was shaped by differential selection and restricted seed exchanges. In their review of crop diversity assessments, they concluded there was a lack of recognition of social identity in the sampling strategy and in the interpretation of results. Thus, G X E are taken into account where regions are geographically based but the sociological aspects are not characterized. They point out the contradiction found in many of these studies listed in Table 3 where the studies have considered fields, farmers production practices, landrace identity, and seed systems but not the social structure in the design. Many of the studies were not able to interpret patterns of diversity or use in the studies to guide conservation in situ or ex situ for the long term.

Westengen et al (2014) concluded that the mechanism of a strong culturally based seed system with a distinct and recognizable sorghum population that was associated with the group was important to the maintenance of the landrace. There was also a need for sufficient heterogeneity to allow for more locally adapted varieties within the landrace. This within population diversity is maintained through the traditional seed system practice of mixing community seed and some degree of outcrossing in sorghum. Despite drought, conflict and relocation of the villages, the local seed system has been resilient with no evidence of significant genetic erosion. Thus, building upon the local seed system and landraces needs to be a consideration in the research and development of sorghum in the future, especially with the challenges of climate change.

Utilization of Genetic Resources

Sorghum is a tropically adapted cereal that has had an extensive widening of its range of production environments during its evolution. This has resulted in a significant focus on the use of genetic resources in the history of crop improvement of sorghum (Rosenow and Dahlberg, 2000; Qingshan and Dahlberg, 2001; Reddy et al., 2008). In the United States, there were limited number of parents introduced from Africa and in the early years of sorghum improvement, this has resulted in a bottleneck that was to be addressed with the development of the Sorghum Conversion Program in 1963 (Steven et al, 1967) to make the more tropically adapted genetic resources available for breeders with the requisite dwarf height for mechanical harvesting and photoperiod insensitivity. This has resulted in new diverse sources of biotic and abiotic stress tolerance being globally available (Rosenow and Dahlberg, 2000). Klein et al (2017) demonstrated that there had been a broadening of the genetic basis of sorghum hybrids in the U.S. with greater use of newly introduced germplasm and the sorghum conversion program has significantly contributed to this. The conversion was not as complete as predicted in terms of the recovery of the exotic parent, but it has increased the genetic resources available.

This importance of genetic resource for the crop’s future improvement was also recognized with the establishment of *ex situ* collections, such as that at ICRISAT in India. Reddy et al (2008) summarized the evaluation and utilization of accessions from the genebank for a diversity of traits by ICRISAT as well as the use of this diversity in the development of improved cultivars, inbred parents for hybrids, and advanced lines. They also review the evaluation and use of genetic resources by the national program in India. Qingshan and Dahlberg (2001) reviewed the history of collections of sorghum in China as well as the evaluation and use of germplasm in the crop improvement programs with a particular focus on using locally adapted accessions. Duncan et al (1991) and Rosenow and Dahlberg (2000) reviewed the utilization of genetic resources for the improvement of parent line in hybrids in the US. In all these reviews, there are examples of the successful utilization of genetic resources for the improvement of sorghum production but also to address significant constraints such as drought, diseases, and insect threats.

While there has been considerable focus on sorghum genetic resources in the past, this has not resulted overall in the extensive use of accessions in collections. One of the issues has been the size of collections, the complexity of the collection, and the lack of information on the accession to aid users in the identification of useful genetic diversity. This has resulted in the development of subset; trait specific, representative, core, or mini-cores. The first sorghum genebank core (or community resource) with associated genomic information for subsequent genetic studies was established by Casa et al. (2008). At present, this reference has been used and cited over 300 times in the literature. These types of diversity subsets are constructed to allow users to identify useful diversity or to identify further sources of diversity in the larger collection with similar traits, origins, or alleles. In addition, with the availability of molecular data, the genetic basis for many of the desired traits can be determined.

Upadhyaya et al (2016) and Upadhyaya and Vetriventhan (2018) reviewed the development of core or representative subsets by ICRISAT, USDA, and others. Billot et al (2013) described the composition of the Global Compositive Germplasm Collection (GCGC) with 3384 cultivated and wild accession that were genotyped to establish a reference set of 383 accession with 78.3% of the allelic variation. The GCGC reference set and the mini-cores established by ICRISAT and USDA for their collections have been characterized, evaluated for many traits, used as association panels, and utilized in breeding. Prasad et al (2021) reviewed the evaluation and breeding for drought and heat tolerance in sorghum. Specific accessions identified for various traits are presented in Upadhyaya et al (2016), Upadhyaya and Vetriventhan (2018) and Prasad et al (2021)

Upadahaya and Vetriventhan (2018) and Ananda et al (2020) reviewed the conservation, evaluation and use of the wild relatives of sorghum. Both reviews included list of wild species that had been identified with traits of interest to breeders and the status of their use. They both concluded there was significant variation within the wild relatives, especially in the tertiary genepool. Both reviews concluded that the wild species were important reservoirs of unique genetic variants but they are currently underrepresented in *ex situ* collections and not adequately protected *in situ* reserves so there needs to be more emphasize on securing their conservation for the future.

Ananda et al (2020) reviewed the research on the barriers to the use of undomesticated species for the improvement of the cultivated S. bicolor. Mainly these barriers are the result of per-and post-zygotic reproductive barriers or pollen-pistil incompatibility. Kulman et al (2010) developed a S. bicolor line that is homozygous to the *iap* (inhibition of alien pollen) gene that reduces this incompatibility so that the pollen grows to completion and hybrids are produced when crossed with species in the tertiary genepool. Ohadi et al (2017) reviewed the use of this gene to transfer traits to cultivated sorghum.

There have been a number of extensive reviews of the genomic resources available for genetic studies and breeding to better link phenotype and genotype, such as diversity panels, reference genomes, and multiparent mapping populations, such as NAM, MAGIC, and mutagenized populations (Upadhaya et al (2016), Hao et al (2021), and Boyles et al (2019). Boyles et al (2019) described the development of these genomic resources in detail and identified the source of the germplasm but they concluded that many of these populations and the corresponding data from their assessments are held by individual researchers or organizations where any change in staff or research direction could result in the loss of critical information for the future. Thus, there needs to be more consideration of secure curation of the seed for these resources and making them more accessible. Curation and warehousing of the key data is also an important for any future use, but this needs to be better coordinated so both the data and the derived lines can be accessed from a central location. This will require clarification on the naming convention and a system to incorporate unique identifiers to codify the phenotyping and any further robust sequencing efforts. Hao et al (2021) also concluded that there is a need for agreed standards for the management, interpretation, and sharing of data. This will allow for rational use without redundant or wasted effort and result in the building of much more knowledge through a community of researchers and studies.

The review by Hao et al (2021) included the application of genomic research within diverse genetic resources, such as the studies reported by Mace et al (2013) Morris et al (2013), and Zhang et al (2018) to dissect the genetic basis for complex traits and population structure. The use of more regional diversity panels has been reported in Maina et al (2018), Faye et al (2019), Girma et al (2019), Cuevas et al (2017), and Cuevas and Prom (2020). Hao et al (2021) summarized the evidence for domestication events and candidate genes in sorghum from genomic studies as well as GWAS, QTL, and transcriptome analysis to dissect complex agronomic traits. They present a table which summarizes the major QTL or genes that have been identified for important agronomic and adaptive traits in sorghum. Hao et al (2021) proposed breeding scheme for sorghum breeding utilizing these genomic resources and genetic selection to develop elite lines from populations developed from wild, landraces and improved lines. They consider there were four key components for these breeding programs that involved diagnosis of the impact of domestication and diversification, description of the genetic and genomic variation, pre-breeding through genomic selection, and finally the use of genomic-assisted introgression. The evidence is summarized for the application of the four components, but they conclude that the application of this modern approach to sorghum breeding was in its infancy so much more needs to be known and developed.

Jannick (2010) predicted that genome wide selection would enable shorter breeding cycles and greater early generation gain prior to the more expensive step of phenotyping but it would also result in loss of genetic variance, loss of genomic selection accuracy, and lead to a low selection plateau. Thus, there is a need to balance selection gain with the maintenance of diversity. Nguyen and Norton (2020) suggested that a breeding approach that utilized high throughput phenotyping (HTP) tools together with genomic selection would result in better gain with less loss of allelic diversity. They present an extensive review of HTP tools applicable to characterization and evaluation for internationally agreed crop descriptors to exploit genebank collections for conservation and for breeding. They concluded that factors that made phenomics applicable to genebanks were cost-efficient HTP technologies available, routine operations that included characterization using internationally agreed descriptors, and focus of genebank on both conservation and use. The concluded that the application of HTP in genebanks would reduce cost and time for these operations as well as increase the consistency and accuracy of characterization for use in selection of accession for breeding programs. It would increase the comprehensiveness of characterization and reduce the lag time to make the information available to users. For breeders, this would increase opportunities to accurately identify the desired accessions and increase gain from pre-breeding or breeding with marginal extra expenses that are now required by users to initially screen a wide array of accessions in order to find those that would be useful. They also concluded that the application of HTP tools to phenotype during regeneration would allow for better monitoring of the genetic integrity of accession to reduce genetic erosion over time as well as allow for identification of accession to be promoted to end users or those that could be archived for the future.

Nyugen and Norton (2020) reviewed the HTP tools now being used by genebanks and identified some key challenges that are shared with the application of geneomic tools in genebanks. This included the challenge of covering the cost for the long-term phenotyping schemes that includes the equipment cost, operational cost, and the cost for for analyzing and making the data available. There are technical challenges for data capture, quality assurance, and analysis for the collection of data, metadata requirements, and data stewardship needs for the long term. There also is also a need to be able to make phenotypic and genotypic data available with the passport data for the end users. They propose a strategic phenomics approach and describe its application at the Australian Grain Genebank in Horshan, Victoria, Australia. They conclude there is a need for coordinated national and international efforts that ensure phenotyping data is comparable across genebanks with an agreed protocols for sharing and exchanging data with unique identifiers and global portals such as Genesys.

So while there are many new opportunities to increase the effectiveness of the use of accession from *ex situ* collections for the future, there are still significant barriers to the current use that has contributed to the limited use of genebank accessions. Gollin et al (2000) concluded that breeders view the use of landraces (and wild relatives) as costly and time consuming with an increased risk of the introduction of undesirable characteristics.

Gollin (2020) concluded this has led to the use of a broad range of diverse accession only for genomics, gene discovery, or more basic scientific research. If they are interested in genetic gain in their breeding program, they utilize improved germplasm. Galluzzi et al (2020) reported on a survey of breeders in 19 countries across a wide diversity of crops on their perception of changes in the climate of their target environments and how this affected their breeding objective as well as the use of specific types of genetic resources. They were also if and how regulatory, financial, technical, and other issues influenced how they use the various types of genetic resources. Both breeders and the farmers perceived changes in the climate of the environment mainly related to rainfall pattern, frequency of drought, and timing of the seasons. The resulted in an increased priority in breeding objectives for pest/disease resistance, drought tolerance, shorter cycles, heat or cold temperature tolerance, and others.

Galluzzi et al (2020) found that with the climate change challenges, breeders had significantly increased use of advanced/elite lines but not in the use of landraces or wild relatives except when faced with more complex climate challenges, they then explored more landrace diversity. They utilized mainly ex situ accessions that came from their own collection or institution (35%), the CGIAR (23%), national genebanks (9.3%), farmers field or natural areas (10.3%) and community genebanks (5.3%). Breeders used different sources for wild species and advanced/elite lines that were mainly sourced from collections outside the country while landraces were mainly sourced from collection in the country. Breeders indicated that the lack of tools for use of germplasm was the most significant issues, for examples, 68% indicated they had limited access to molecular tools and approaches while 24% said they had a lack of infrastructure for phenotyping, controlled trials, and characterizations. Only 6% of the breeders indicated that the availability of genetic material or the information on them was a critical limitation. The prominence of the CGIAR as a provider of germplasm has decreased and this is probably due to the large number of transfers that have already happen in the past. Galluzz et al (2020) concluded that the survey indicated that the lack of supportive policy and/or administrative environment was more of a barrier to the use of germplasm than technical capacity. This needs to be addressed with greater national and international collaboration.

Conclusions

Sorghum is an important cereal crop, especially for subsistent farmers in South Asia and Africa. In some other areas of the world, such as the United States, Mexico, Argentina, Brazil, Australia, China, Japan, and other areas of the world, it is an important feed crop with a significant value for trade. The areas of production for sorghum have declined in most regions of the world except Africa, where it is an important for household food security and as a contributor to poverty alleviation, but it also has significant cultural value.

The cultivated crop, *Sorghum bicolor* subsp. *bicolor* has significant genetic diversity but the wild and weedy subspecies is a source of additional, potentially useful allelic diversity. There are also many related species that have unique traits and adaptation that could serve as a source of improvement in the future. The diversity within landraces is extensive and is a product of differences in genotypes, environments, and social systems. There have been a few studies on changes in landrace diversity in the field over time but there has not been an assessment of genetic erosion that needs to be urgently addressed. The use of genetic resources in the improvement of sorghum production has been important in the past and is recognized as a key resource for improvement in the future with the many challenges and/or opportunities like climate change but also new uses for the crop. The breeders of the crop continue to put high priority on improving traits related to changes in the climate of the target environments, such as drought tolerance, cold or heat tolerance, pest/disease resistance, or the need for shorter duration varieties. This need has resulted in an increased use of genetic resources such as elite lines from other breeding or research programs, landraces sources from local farmers, and wild relatives. This increased interest of the users of genetic resources presents both future opportunities for *ex situ* collection holders but also challenges to meet the needs of the end users.

Gollin (2020) concluded that the assumption of the most useful diversity to conserve for long -term use will need to be challenged as will our understanding of what the future user of the collection will need. Both Gollin (2020) and Smale *et al*. (2021) concluded that as we consider the value of the accession conserved as well as the information for the future user, we will need to reconsider the priorities for future collection and long-term conservation for the different types and origins of genetic resources for sorghum. The greater application of genomics and HTP phenotyping (Shakoor et al. (2015); Shakoor et al. (2017); and Wang et al. (2018) will benefit both the end user and the genebank operations, but this will challenge the capabilities of the curators, the data management system, the global sharing of data, and the curation of this data. It will require much greater links between genebanks, between genebanks and users, and between users, nationally and internationally. These challenges were considered in the 2007 strategy but only from the view of the genebanks and without the benefits of the technological advances currently employed by the user community that have occurred in the last 15 years.

Status of *Ex Situ* conservation– Composition

A very important input into a global conservation strategy is the survey of the current collections holders to determine the status of ex situ conservation and use of sorghum genetic resources. In 2007, there were 122 different collection conserving 194,250 accessions. The collections were prioritized based on size and likely contribution to global diversity from the landrace/wild complex. A survey was sent to these 57 priority ex situ collections and 19 of these responded. The experts at a consultation workshop considered a major collection to have a significant sampling of diversity, accession level characterization and evaluation data accessible and available, and access and availability of accession with their associated information. They considered the ICRISAT and USDA collections as major collections. They also consider other collections as important, especially those in the primary and secondary center of diversity or specialized collection such as the broomcorn collection in Serbia. They identified 21 collections that were important and where information on the status was needed.

In 2021, the 135 institutions that currently conserved sorghum were prioritized and 58 were identified for follow-up with the survey. A priority genebank had to meet at least one of these criteria.

- more than 500 accessions reported in FAO-WEIWS and/or the Genesys,
- was known to conserve significant local diversity of specialized accessions
- was recognized as a major or important collection in the 2007 strategy.

For the update of the global strategy, a survey was sent to priority genebanks. The questionnaire differed from the 2007 survey with a greater focus on the composition, the status of the various routine conservation activities, and the specific user of the collection. We received responses from 37 institutions and the contact details are given in Annex 1.

The number of accession conserved ex situ reported in the 2007 and/ or 20212 survey, or the FAO-WEIWS/GENESYS database is given in Annex II. There were several collection holders who did not respond to the survey nor report into the FAO-WEIWS or Genesys database. The most significant were CAAS in China, VIR in Russia, CIRAD in France, Institute of Field and Vegetable Crops in Serbia, and the national genebanks in Rwanda, Yemen, and Guatemala. There were other important collection holders who did not respond to the survey but there is accession level information available in FAO-WEIWS. These were the genebanks in Japan, Hungary, Bulgaria, and Pakistan. In 2021, there were 10 institutions that reported only to this survey. When the number of accessions were compared for 2007 and 2021, eight institutions had a significant reduction in the number of accessions. This is a concern that could be due to challenges that genebanks that threatens the sorghum genetic resources they conserved. This will be explored in more detail in the strategy as we consider the vulnerability of the global system to genetic erosion.

So overall, the survey respondents conserved about 80% of the global accessions with very good participation except in the European region where only 2 institutions responded that only held 2% of the accessions from that region (Table 4). This is a region that is characterized by many smaller collections that account for only 5% of the global accessions. There are some important collections in this region that hold a broad base of diversity and some specialized collections. In the other three regions, the survey respondents conserved close to 100% of the accessions in the region.

Table 4. Regional distribution of institutions and accession conserved in consolidated FAO-WEIWS/Genesys database and the 2021 survey respondents

Global regions	**Consolidated FAO-WEIWS/Genesys database**		**2021 survey respondents**	
	No. of countries	No. of accessions	No. of countries	No. of accessions
Africa and Middle East	47	53024	26	52705
Europe	41	13880	2	323
Asia Pacific	21	133652	5	107255
America	26	59039	4	55118
Grand Total	135	259595	37	215401

Generally, in the survey, there are few accessions of the wild species conserved ex situ, especially in Africa for the wild and weedy subspecies of Sorghum bicolor (Table 5). The only exception is for the respondents from Europe where other Sorghum species are the prominent type of accessions. This could also be an indication of the low participation form Europe. Most of the accessions conserved globally are farmer varieties or landraces that have been collected in the country of the institution in Africa and Asia-Pacific, while the highest number of land races acquired from others were in Asia-Pacific. There is a higher number of released varieties and breeding material conserved in the Americas and those that are not classified. So globally, landraces are the predominant type of accession being conserved.

Table 5. Regional distribution of type of accessions conserved by the survey respondents

Global regions	Landraces collected in country	Landraces acquired from outside country	Old cultivars and released varieties	Research or breeding advances lines, populations or genetic stocks	*Sorghum bicolor* subsp *verticiliflorum* and *drummondii*	Wild relatives in other *Sorghum* species	Not classified
Africa and Middle East	30172	10526	716	2384	495	169	3585
Europe	61	18	3	0	5	234	2
Asia Pacific	44354	37276	808	13125	657	413	10622
America	110	2576	2454	19437	338	120	30083
Grand Total	74697	50396	3981	34946	1495	936	44292

Given the extent of conservation of farmer varieties acquired from others and the conservation of research products, there could be significant redundancies in the global system. In the consolidated database, 73% of the accessions have information on the country of origin. In most cases that is the origin from collection or breeding but sometime this is the origin of the donor. This is especially the case for accessions originating from the

USA, India (ICRISAT), and Australia. Despite this shortcoming, this accession level information does allow the assessment of potential redundancies and gaps based on geographical origin of accessions conserved. There were twenty institutions that conserve accessions originated from 108 to 8 countries geographical diversity. Some of these, ICRISAT, ICBA, the SADC regional genebank, and ILRI have been established as international or regional collections. There were two institutions that conserved very small collections. Table 6 list the 14 institutions that conserve geographically diverse collections. These are all national collections and some like the national collection in India (NBPGR), Kenya (KLRO-GRRI), and Brazil still conserve more than 60 % of accession from the country. These 18 internationally diverse collections conserve about 45% of the global accessions. When you consider the proportion of accession held from each country, there are 58 countries where these 18 genebanks conserve all the global accessions that ranges from nearly 7000 accessions from Yemen to less than 5 accession for 18 of these countries. There are 15 countries where from 0 to 25% of the accession conserved globally are being held by these institutions. These 18 international collection are a key component of the global system, then further analysis of their duplications would allow for a much better understanding of the duplications globally

Table 6. The number of accessions with country of origin designated, the number of countries of origin, and the proportion of accessions that derived from the country of the institute.

Institution	**Number of accession with country of origin**	**Number of countries of origin**	**Proportion from country of institute**
USA016	38404	108	13.1%
AUS165	5731	79	20.8%
UZB006	662	48	5.0%
HUN003	612	38	17.5%
GBR004	235	26	0.4%
BGR001	333	33	6.6%
DEU146	336	29	2.4%
CZE122	60	14	3.3%
ROM002	49	16	38.8%
BLR026	152	13	34.2%
UKR005	197	29	56.9%
IND001	16845	47	65.7%
KEN212	5257	18	76.1%
BRA003	2649	8	62.1%

There is also evidence of a high degree of duplication for accession from a limited number of countries. There are 11 countries that are the most represented in the global system as source of accessions and account for about 40% of the accession conserved globally (Table 7). The number of accessions from India includes ICRISAT which is the origin for about 30% of the accessions from India. Some countries, such as the USA or Australia were not included since they are more likely to be the source for acquisition. Although this is just the number of accessions by the country of origin, this assessment does demonstrate the potential redundancies in the global system when you consider that many collections have been done jointly with other collection holder, the accession was conserved by both, and then distributed to others.

Table 7. The number of accessions conserved and the number of institutions conserving for eleven of the most frequent countries of origin.

Origin	No. of accession conserved globally	No. of institutions conserving
India	24722	18
Sudan	20269	16
Ethiopia	22168	15
Kenya	6795	11
Mali	6321	15

Zimbabwe	6265	11
Nigeria	5697	12
Uganda	4486	12
Tanzania	2989	13
South Africa	2857	14
China	2216	15
Total	104785	

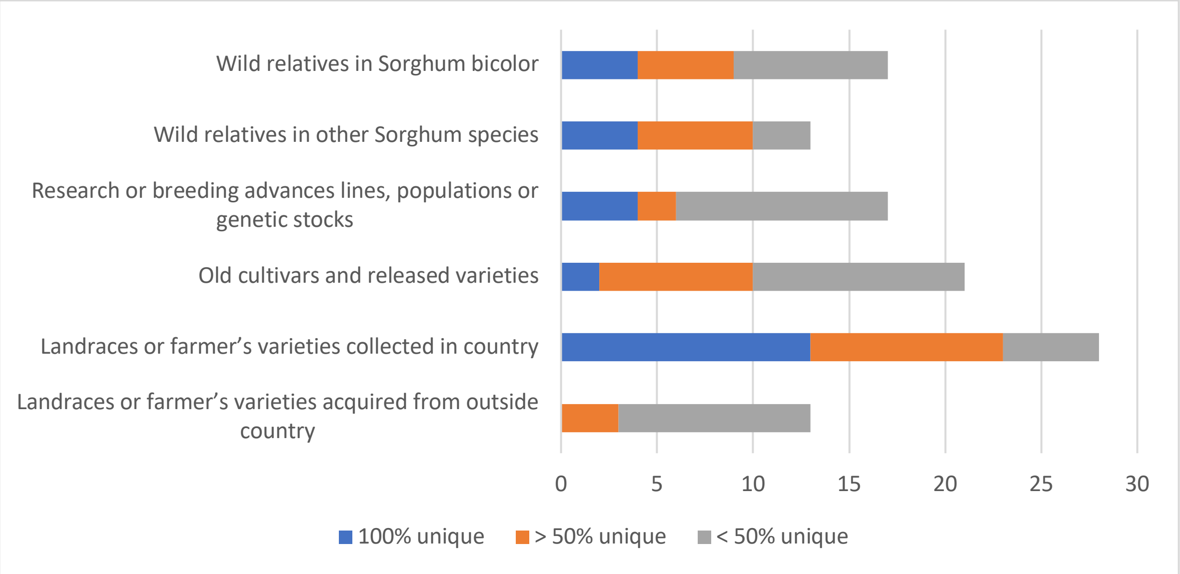
An assessment of the geographical origin of accessions in collections also indicates significant gaps in conservation or collection. In Table 8, the number of accessions conserved globally, the number of institutions conserving and the proportion that is being conserved nationally is given for 25 of the countries that responded to the survey. Redundancies can be considered as a positive feature of the global system in terms of the security of conservation for collections or localities at risk of loss but it also complicates the use of the collection, especially without additional and informative accession level information. Table 8 also gives an indication of some significant gaps in conservation for specific countries and localities, for example, there are very few accessions from Eritrea that are conserved outside Eritrea. There are seven countries where more than 50 % of the global accessions are conserved nationally. If these are not adequately safety duplicated, this could be a risk for these national collections.

Table 8. The number of accessions conserved globally from the specific country, the total number of institutions conserving accession that have been sourced from that country, and the proportion of the global accession that are conserved in the specific nationally based institution.

Country	Number of accession globally	No of other institutions conserving	Percent held by nationally based Institute
Eritrea	724	1	99.7%
Spain	79	2	77.2%
Sri Lanka	110	4	73.6%
Nepal	83	4	72.3%
Niger	5671	6	60.7%
Kenya	6795	10	58.9%
Senegal	1539	9	51.4%
Lesotho	856	5	47.4%
Ethiopia	22168	14	45.1%
Ghana	757	7	44.8%
India	24722	16	44.7%
Morocco	89	9	41.6%
Mali	6321	14	40.9%
Botswana	1197	8	40.4%
Nigeria	5697	11	39.8%
Namibia	535	4	35.5%
Sudan	20269	15	35.5%
Burkina Faso	3778	8	34.9%
Zambia	2924	6	32.8%
Zimbabwe	6265	10	32.4%
Chad	526	4	26.4%
Uganda	4486	11	21.2%
South Africa	2857	13	19.4%
Benin	509	2	16.9%
Togo	1016	2	15.4%

The survey respondents were asked to do a self-assessment of the degree of 'uniqueness' of the type of accession they conserved. The categories included fully unique, more than 50% unique, and less than 50% unique. Very few respondents concluded the wild relatives, breeding material, or old cultivars accessions were fully unique but about half rated the landrace collection in their countries as unique. In general, the respondents in the survey concluded there was duplication in their collections. The results would indicate that they also considered the origin of the accessions and if they were known to be duplicated at other genebanks. The number of respondents that consider their accessions unique was mainly for accession collected in the country and the wild relatives. Although there were genebanks that considered the research products as unique.

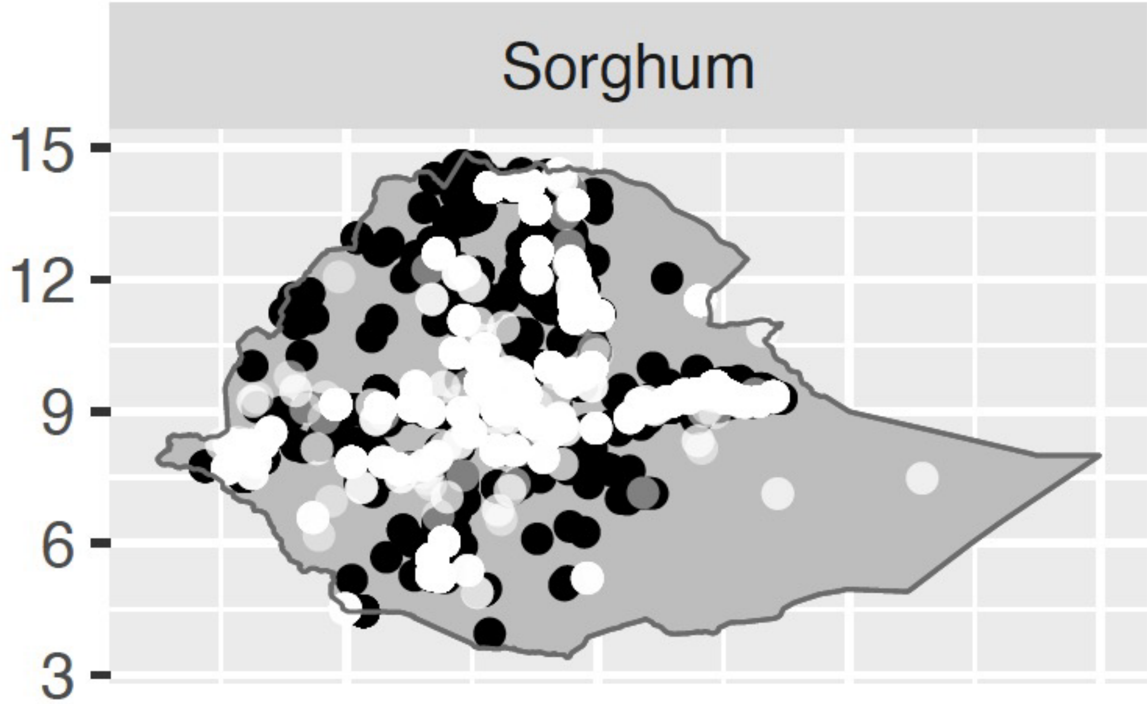
Figure 2. Self-assessment of 'uniqueness' of accession by institutions in the survey



To further assess this, it is necessary to utilize accession that are georeferenced in the consolidated database and this allows for a global assessment of the duplications and gaps. Many accessions from Ethiopia are conserved globally and about 45% are conserved nationally by EBI (Table 8). In Figure 3, the location for accessions conserved by EBI is indicated with black dots while those conserved by other genebanks is in white (Cite Nora for SfR project). There is significant overlap for these accessions overall but there are localities of Ethiopia where the only accessions conserved globally are conserved at EBI and a few localities where the accessions are only conserved outside Ethiopia. There are also localities that are likely not conserved by EBI but only by local farmers. This assessment of global gaps would allow for a much greater targeting for collections and for safety back-ups if needed.

Figure 3. Distribution of accession collected and conserved from Ethiopia by EBI and by others[1]

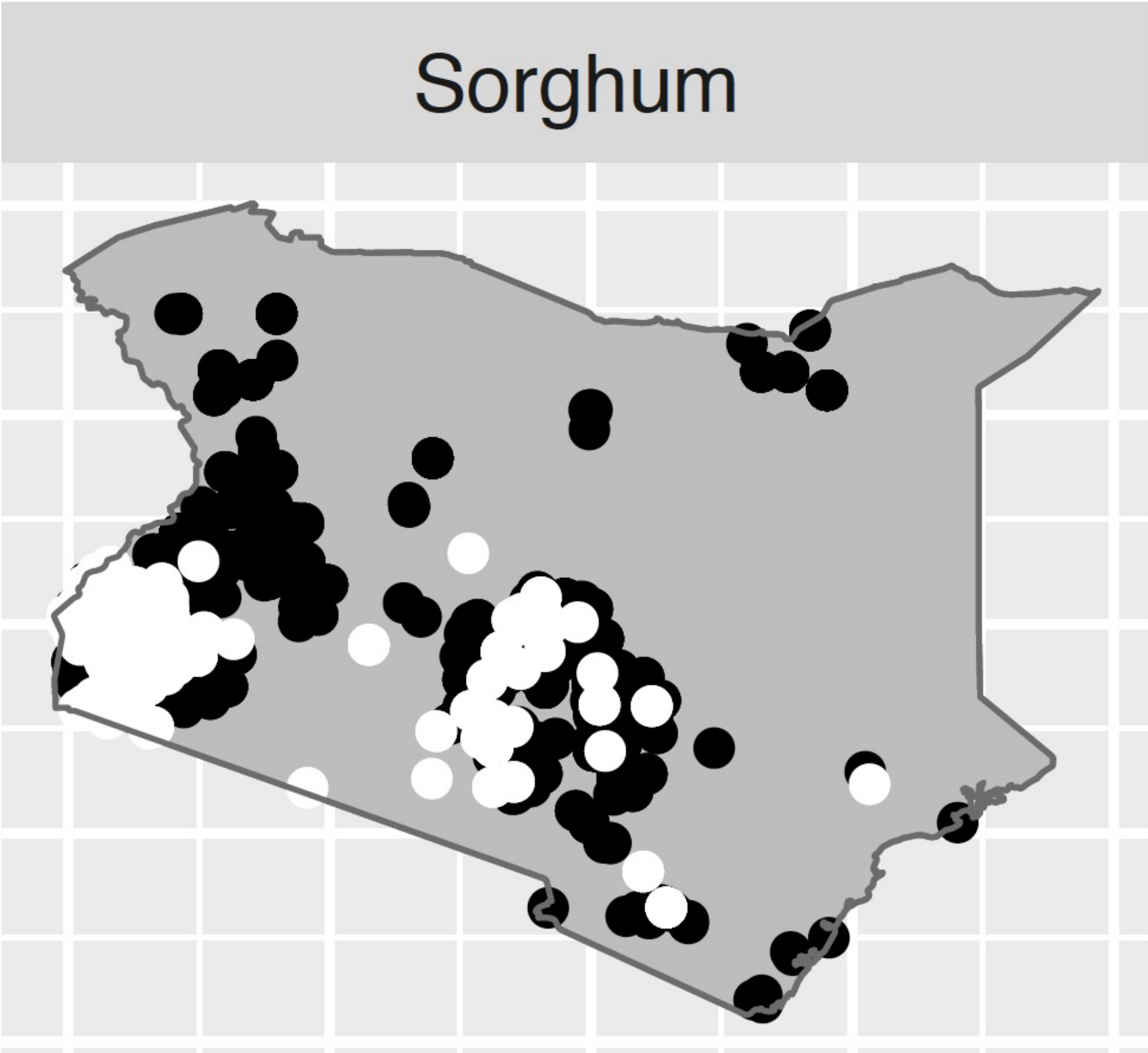
[1] Black points represent the accessions held at EBI, white points represent the accessions held at other genebanks outside Ethiopia.



In another example, the KALRO/GRRII conserves about 60% of the global accession from Kenya (Table 8). In Figure 4, there is significant overlap between all the accession held globally and that in the national collection, especially in the southwest corner and the central areas of Kenya. There are also many localities where the national genebank conserves the only accessions and these should be a focus for safety back-up. There are still localities where the local genetic resources are only conserved by the local farmers or in natural areas. Again, this demonstrates the value of global assessments of gaps that consider accession conserved by all collection holders, not just national or international genebanks.

Figure 4. Distribution of accessions originating from Kenya and conserved by KALRO/GRRII in Kenya or by other genebanks outside Kenya. [2]

[2] Black points represent the accessions held at KALRO/GRRII, white points represent the accessions held at other genebanks outside Kenya.



While there are clear global gaps in collections related to the low number of accessions conserved globally or nationally, there are also gaps due to the insecure status of conservation. Even in countries with a high degree of redundancies globally, there are gaps in localities nationally. In the 2007 Strategy, there was a recognition that the high degree of duplication made it complicated to interpret the adequacy of the diversity and coverage of the accessions conserved globally. This was due to the low availability of passport data from many collections and the number of accessions that were in common with the country of origin, the USDA collections and ICRISAT. This is still an issue for this 2021 assessment. The expert workshop in 2007 concluded there was a need to assess the level of duplication between the major collections by assess the collection information and determine duplication for the ICRISAT and USDA collections, then develop datasheet that would assist curators for other collections to correct data and determine duplications with the ICRISAT and USDA collection and finally utilize the global accession level information system to identify probably duplications. This was identified as a priority action for the global system, but it seems this was not done. The 2007 strategy also identified gaps based upon expert knowledge and these were Liberia, Ivory Coast, Guinea, DRC, Ghana, Nigeria, and along the Niger river delta as well as Central America, Central Asia and the Caucasus, and Dafar in Sudan, and South Sudan. The wild species coverage was also viewed as inadequate.

In the 2021 survey, the respondents were asked about the assessment of redundancies and gaps in the past 20 years. There had been a few cases of assessment done on redundancies. IIMR in India had found that 15-20% of their collection was also conserved by

NBPGR and ICRISAT, based on the passport data. NBPGR had also utilized passport data to assess duplication with ICRISAT collection. INIA in Spain had utilized Genesys to assess duplication in their collection. AGG in Australia is planning to use passport data and some genomics to do an assessment of duplication in their collection. In Burkina Faso, they utilized variety names to assess duplication. Several the respondents recognized that there was duplication with other collections that were viewed as safety duplicates for the future.

Gaps in collection were also assessed by some of the respondents and some effort was made to address these with collection, especially by ICRISAT and the national genebanks in Africa. The gaps were assessed using GIS for ICRISAT, IIMR and NBPGR in India as well as some of the countries in Africa. Gaps were being filled for these individual collections. Some countries identified that they did not have geographical gaps nationally, such as Nepal, India, and South Africa. In other cases, gaps were targeted using expert knowledge, morphological characterization, stakeholder consultations, specific traits identified by users, and distribution of local production. Some of the gaps were for collection and others were for acquisition. When the gaps identified in the 2021 survey were compared with the 2007 report, it seems that many of the gaps in West and Central Africa remain as does South Sudan. There are also significant gaps remaining in many other areas of the world based upon the assessment of the consolidated database for Central America, Central Asia, and the Caucasus. Finally, the species coverage is still seen as inadequate as well as ecological sampling at the national level.

Assessing gaps in ex situ collections has been seen as important step for the rational enrichment of the diversity or coverage for individual collection. Upadhyaya and Vetriventhan (2018) reviewed the application of gap analysis in the ICRISAT sorghum collection for South Asia (Upadhyaya et al 2016), East Africa (Upadhyaya et al 2017a), West and Central Africa (Upadhyaya et al 2017b), and Central Africa (Upadhyaya et al 2017c). These studies utilized accession level passport and characterization data to assess the distribution of diversity within the target region. The assessment utilized a set of accession that were known to originate from the target region and then did the further analysis on a smaller subset of accession where the data was complete for GIS, race classification, or other characterization data to allow for differentiation of the accessions across the region. The general approach taken to assess gaps was initially just target localities where no accession were being conserved, then determine the degree of representation in the other localities to target those with very limited sampling, then utilizing the characterization data to target localities with the greatest species richness or morphological diversity, and finally utilize ecological modeling to identify geographical areas with likelihood to sample unique ecotypes or populations. These steps were used to identify gaps for collection in the future but mainly focused on the localities where no accession had been collected.

One key constraint for assessing gaps utilizing this approach was discussed by Westengen et al (2014) and Leclerc and d'Eeckenbrugge (2012). There is an assumption in the studies reviewed by Upadhyaya and Vetriventhan (2018) that the main factor differentiating diversity in sorghum populations is geographical distance and ecological adaptation but Westengen et al (2014) that the structure of sorghum diversity in Africa was most strongly association with social and cultural factor while the geographical distance and ecological adaptation, and even morphological traits were contingent on the social structure. This was also discussed in detail by Leclerc and d'Eeckenbrugge (2012). Thus, an assessment of gaps in individual collections utilizing limited subsets with adequate data for geographical or morphological structuring is not a satisfactory approach to assess the adequacy of global coverage of diversity and the significant gaps in conservation, either ex situ or in situ. The assessment of conservation priorities for the wild Sorghum species reported in Myrans et al (2020) utilizes geographical and ecological factors that demonstrate the global gaps in conservation for species where they are likely the main factors responsible for population structure. They identified taxa that were a high and medium priority for ex situ and in situ conservation.

In summary, individual collection composition is a product of its history and the past objective for ex situ conservation. Upadhaya et al (2017c) reviewed the history of the accessions from West and Central Africa in the ICRISAT collection. Most of the accessions were donation from 24 institutions and only about 20% were from collection missions. Thus, the collection is biased towards the focus for the donations and these missions. Gollins (2020) concludes that an ex situ conservation strategy that focuses on conserving everything needs to be reconsidered if we are to meet the need for conservation and use in the future. As we gain a much greater understanding of genotypic or allelic diversity through enhanced genomic tools and the application of estimates of social and cultural diversity, it is feasible to utilize a global approach to the identification of duplications and gaps that will build upon greater collaboration and information sharing to address a global need for a more rational, cost-effective conservation and use system for sorghum genetic resources.

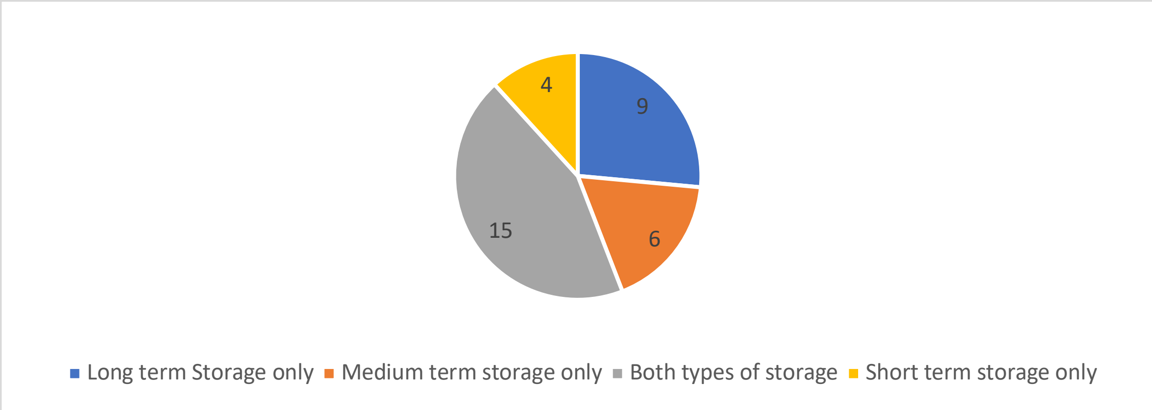
Status of *Ex Situ* collections –Conservation

Sorghum bicolor has an orthodox seed that is tolerant to drying to a low moisture content and being stored for very long periods under low temperatures if the seed is of high quality and viability. Some of the other *Sorghum* species have low seed sets and seeds that are not very tolerant of these storage conditions and thus must be maintained in field collections. The routine conservation of sorghum has similar operations as those described for seed genebanks in Hay and Sershen (2021) and Engels and Ebert (20201b). A key input into the development of the global strategy is an assessment of the efficiency, effectiveness, and security of conservation amongst the current *ex situ* collection holders. To do this assessment, the survey to collection holders included questions related to the routine operations being conducted and to what degree; the type and state of the facilities; type of conservation research; and the security of conservation.

Conservation infrastructure

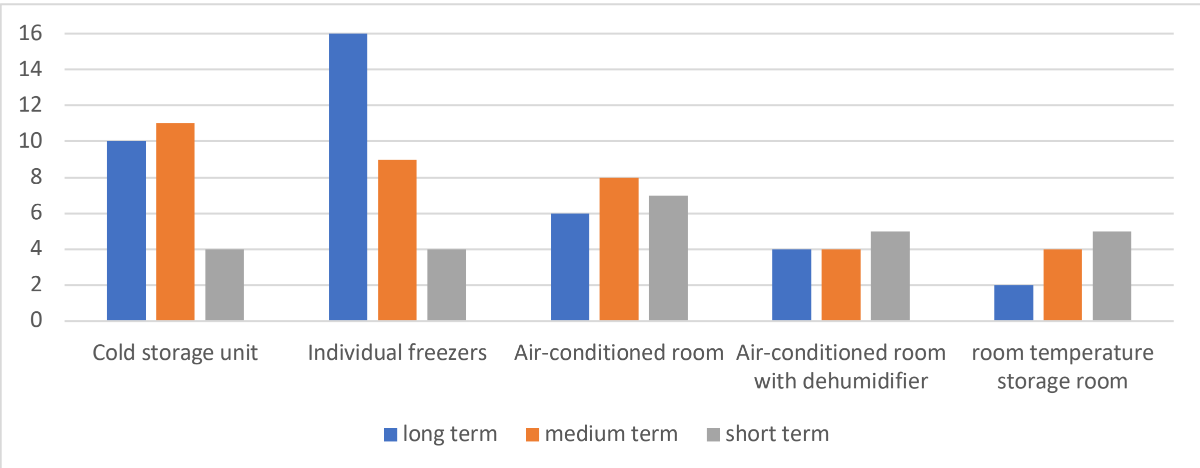
Most genebanks conserve accessions in active collections, base collections, or both. Active collections are typically conserved for the medium term at temperatures of 2-4 C while the base collections are conserved for the long term at low temperatures, mainly -18-20C. Thus, one of the key infrastructure needs are cold storage units. Hay and Senshen (2021) describes the use of medium-term storage as a cost-effective way to conserve seed that will be distributed while the long-term storage will maintain seed viability for much longer. Nine of the institutions in the survey conserved the accession in only long-term storage while seven of the respondents only had medium term storage (Figure 5). Four of the institutions had to store seed at ambient temperature since they had no access to reliable cold storage. FAO (2014) indicates that storage of seed at ambient temperature could be used to maintain viability for eight years of so, the temperature needs to be kept as cool and stable as possible. If not, then the storage will require frequent regeneration of the accession to maintain viability.

Figure 5. The number of institutions that utilize long-term, medium-term, both long-term and medium-term, or short-term storage for conservation (n=28)



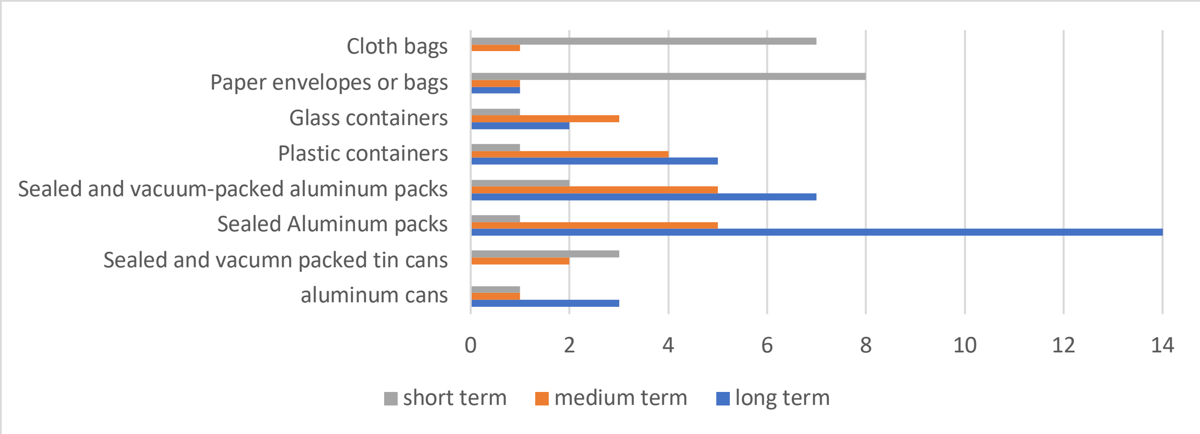
The efficiency and security for the routine conservation operations is dependent upon having trained staff with adequate facilities, equipment, key consumables like packaging, and procedures or processes. The institutes classified the types of storage facilities they used for long, medium, and short-term conservation. Cold storage units were used for both long term and medium-term conservation, but individual freezers were the more frequently used for long term conservation. FAO (2014) indicate the storage conditions need to be more stringent for the most original samples and the safety duplicates. The warmer temperatures used for medium term storage are appropriate for the samples that will be more frequently distributed, multiplied, and characterized. Using a room with air-conditioning to maintain a stable temperature and sometime a dehumidifier to control the moisture content was a storage option for a small number of the institutions. Unfortunately, a small number of institutes stored seed at ambient temperatures. These lower standard storage units would not be considered secure for the longer term but could be adequate depending upon the objective of conservation.

Figure 6. Type of storage used for sorghum seed conservation (n=28).



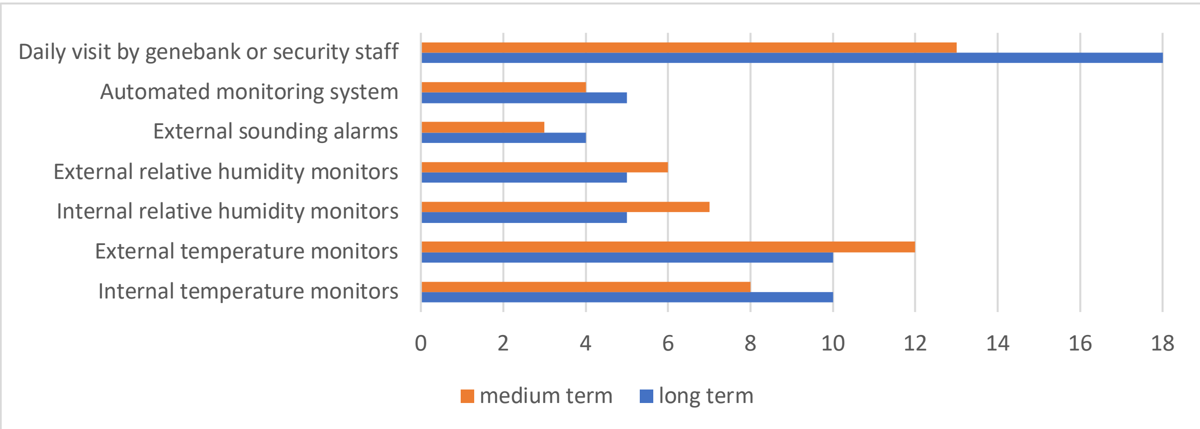
The FAO (2014) international standards for genebanks indicate that airtight packaging is necessary for long term conservation to minimize loss in seed viability. They only recommend non-airtight packaging for medium-term conservation where the seeds are accessed to distribute fairly frequently. In the survey for long term conservation, most of the respondents used sealed aluminum packs with or without vacuum packing (Figure 7). The use of aluminum packs would indicate that the seeds were being appropriately stored if the packs are of sufficient thickness and sturdy (multiple layer material). The lack of vacuum packing would indicate the need to use airtight packaging to meet international standards for long term storage. A smaller number of the institutes also used aluminum cans, plastic containers, and glass containers. For short-term seed storage, the institutes mainly used cloth bags and paper envelopes or bags.

Figure 7. The number of institutions that store seed in different type of containers for long-, medium-, and short-term storage (n=28)



The FAO (2014) genebank standards suggest the need for monitoring devices for temperature and relative humidity to track the actual parameters over time. This is best done with monitoring devices inside the storage unit and an external readout to allow for monitoring without opening the unit. These then need to be reviewed on a regular basis to identify issues with fluctuation. All the institutions had monitoring of the seed storage units, although six only utilized daily visits by the genebank or security staff. Three genebanks had monitoring of internal temperature but not daily visit of staff to review the monitors. So while 18 of the institutions had internal monitors for freezer or cold storage units, fewer had external monitoring of the temperature, especially in the long-term storage unit (Figure 8). Fewer of the respondents monitored relative humidity than monitored temperature.

Figure 8. The number of institutions that utilized various approaches to monitor long=term and medium-term seed storage units of the genebank (n=28).



FAO (2014) indicated that fluctuation in temperature and relative humidity in refrigerated storage was more detrimental to seed viability for the long term than no refrigerator storage at all. Thus, they recommend back-up power supply to ensure a constant temperature and relative humidity. Backup generators were used to secure seed storage units by 15 of the institutions while 13 of the institutes who utilized a cold storage unit or a freezer had no back-up generator. For many of these respondents, the back-up generator was at least adequate but there were constraints such as the lack of funds for maintenance, repair, and replacement, and the lack of an automatic on/off system for the generator.

The international standards indicate the need to have adequate security for monitoring and protecting the collection. The main approach that the respondents used was daily visit by genebank staff or security staff. These visits are adequate if they are frequent and if there are logs kept of the status. There also needs to be an adequate protocol for ensuring that action is taken quickly to rectify issues. This was not explored in the survey. Only about 21% of the institutions utilized an automated system for monitoring but that number should increase as the technology is readily available. This approach should be more secure since the monitoring devices would also be recording the fluctuations in temperature and relative humidity as well and would be 24 hours and seven days a week.

Another source of risk for genebanks is the impact of inadequate infrastructure and equipment as well as the lack of appropriate facilities for the routine operations. The twenty-eight respondents were sub-divided to those which maintained more global collections (n=6) based upon the geographic diversity of the country of origin of their collections and those that had a more national focus (n=22). The response of the institutions is given separately for these two categories in Table 9. Only one of the global genebanks rated their facilities and equipment as inadequate. More than a third of the national genebanks rated their equipment and facilities as inadequate. In both categories of genebanks, the age of the facilities and equipment varied from 6-40 years, and some indicated there was ongoing effort to renovate the facilities and replace the equipment. For those who had constraints, the main issue related to a lack of adequate funds to upgrade or replace facilities and equipment, issues related to electricity supply, and inadequate space in the genebank or dedicated space for the essential laboratories.

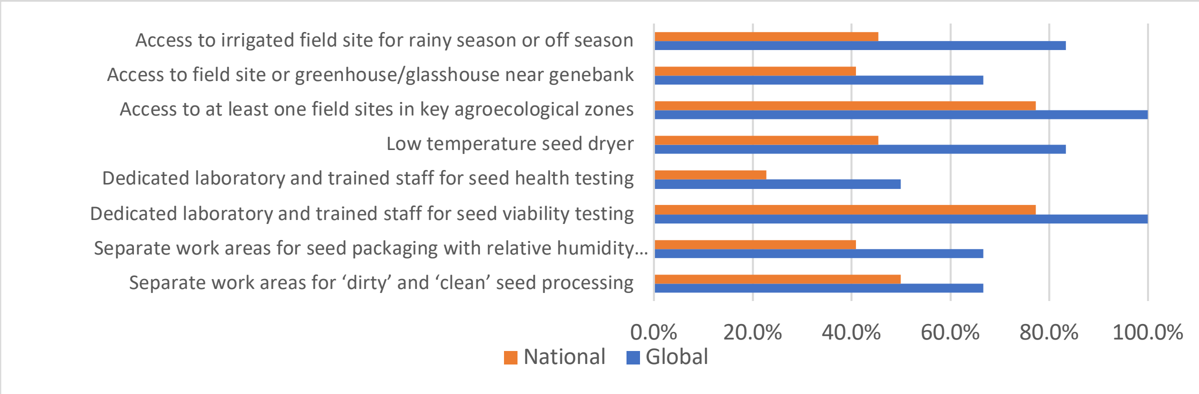
Table 9. The number of institutions that rated their facilities and equipment as excellent, adequate, or inadequate (n=28)

	Genebank buildings and facilities	Storage facilities	Laboratory facilities	Laboratory equipment	Field equipment	Generator
Global						
Excellent	4	2	2	2	3	3
Adequate	1	3	2	3	1	2
Inadequate	1	1	1	1	1	1
National						
Excellent	2	2	2	2	2	1
Adequate	10	10	10	9	7	6
Inadequate	8	8	7	7	7	8

In the future, genebanks will need to consider their carbon footprint and the routine cost for meeting their power requirements for securing the long-term conservation of their collection. The shift to alternative energy supplier such as solar could address this need as could the investment into energy efficient equipment for new or replacement purchases. Three of the institutions had already shifted to solar power for the genebank or at least for a specific facility in the genebank. More than half of the institutions indicated that energy efficiency was a criterion for procurement of equipment.

The institutions were also asked about access to the specific types of facilities, equipment or field space to allow them to meet international standards for their routine operations and secure conservation for the accessions (Figure 9). In general, a higher proportion of the global institutions had access to the facilities, staff, and equipment. Given the important of seed drying for the long-term conservation of sorghum seed, only half of the national institutions had a low temperature seed dryer. Having the appropriate work areas for the different seed handling operations is also important for seed quality but in both groups, this was still lacking for more than 30% of the institutions. While access to laboratory and facilities for seed viability testing was from 75-100% for both groups, a much smaller percentage had access to seed health testing facilities and staff. These responses indicate that many of the national genebanks lack space, facilities, and equipment to meet international standards for conserving orthodox seeds.

Figure 9 Proportion of institutions within the global and national category who indicated they had the specific facilities, equipment, or access to space. (N=28)



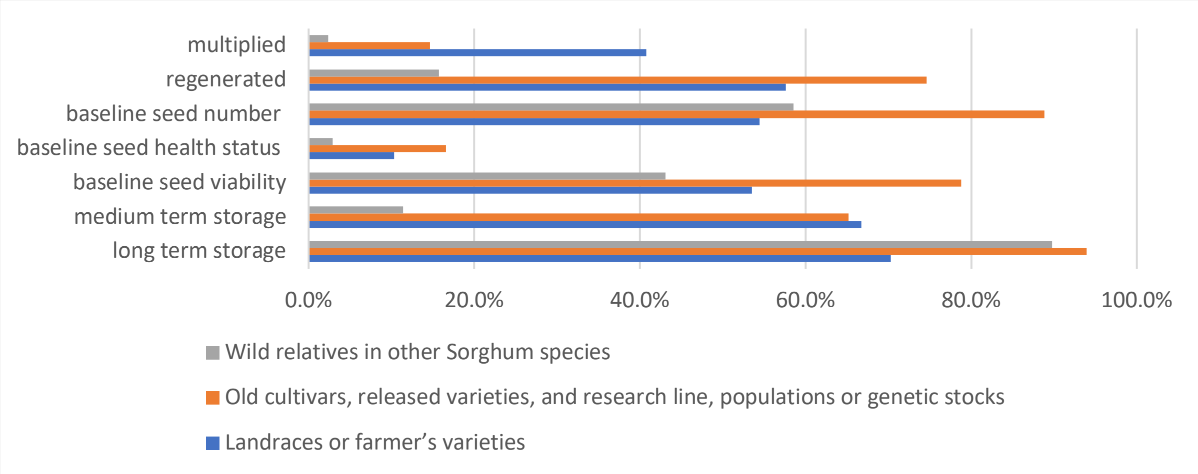
Secure regeneration will require access to the appropriate site for regeneration and access to facilities that will allow for regeneration of difficult accession or those in need of urgent regeneration. While 100% of the global institution had access to appropriate sites for regeneration, about 60-80% did not have access to the appropriate site for securing regeneration for those accessions that with very low seed viability or seed quantity or are difficult to grow. A higher proportion of the national institutions had inadequate access to the appropriate sites for regeneration in general.

Routine conservation operations

An assessment was made of the number of accessions conserved by the institutes that are being conserved long-term or medium term. Also, the number that have been tested for seed viability and seed health, and the number of seeds determined, and the number of accession that had been regeneration or multiplied, and characterized for minimal traits. Overall, about 80% of accession are conserved in long term conservation, 63% in medium term conservation, 62% of the accessions have baseline seed viability test done, 10% of accession have baseline seed health test done, 67% of accessions have seed number determined, 57% have been regenerated, 28% of the accession have been multiplied for seed increase and 77% had been characterized for minimal traits.

The survey also requested the status of the routine operations be reported separately for the different types of accession; landrace or farmer's varieties, research products such as old cultivars, released varieties and research lines, population, or genetic stock, and finally for the wild relatives. The proportion of accession in each of these types that have been processed for each of the operations is given in Figure 10. No germplasm type had a significant proportion of the accession assessed for seed health. The accessions from the research type had the highest proportion for each operation except for multiplication. This could be an indication of the greater distribution and use of this germplasm type. About 70% of the landraces are conserved in long- and medium-term conditions but only 40-50% have had the seed viability and seed number determined or been regenerated or multiplied. A high proportion of the accession of the wild relatives are conserved in long term conditions with a moderate proportion that have baseline seed viability and seed number. It is probably not surprising that less than 20% of the accession have been regenerated or multiplied given the difficulty in handling these in the field or greenhouse.

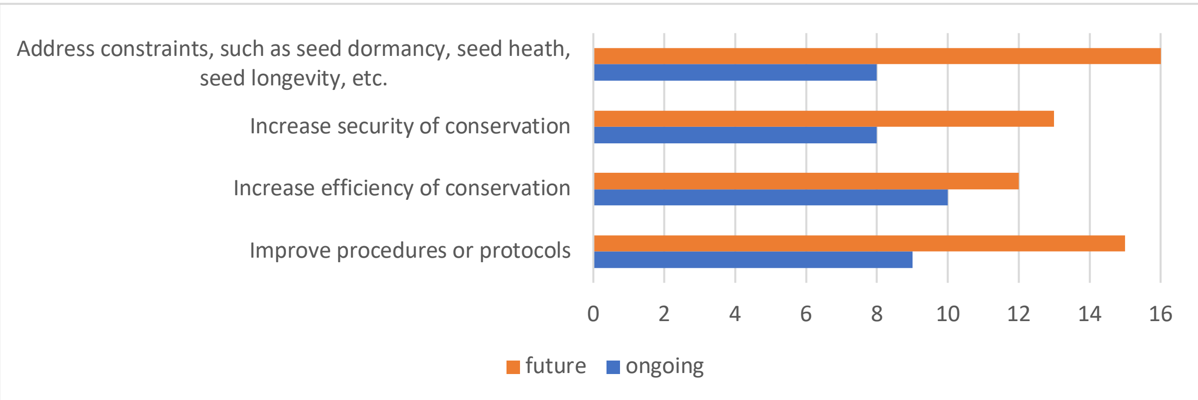
Figure 10. The proportion (%) of landrace or farmer's varieties, old cultivars, released varieties, and research lines, populations or genetic stocks accession over all institutions that are conserved in long term and medium-term conservation as well as assessed for baseline seed viability, baseline seed health status, baseline number of seeds conserved, and have been regenerated and multiplied.



The respondents were asked about the written procedures and protocols used in the routine operations of the genebanks. Only, five of the institutes indicated had no written procedures or protocol. Seventeen of the institutes indicated they use the procedures and protocols given in Rao et al (2006) while ten institutions utilized an earlier manual by Hanson (1985). About one quarter of the respondent had their own genebank operational manual and/or written standard operating procedures for key processes. Five of the institutes utilized a quality management system (QMS) or they utilized the FAO (2014) international genebank standards which are not written procedure or protocols but recommendations standards to meet.

Finally, the survey asked if the genebanks had ongoing research on conservation or if they had the expertise to do conservation research for the future. The question identified four possible areas for research in conservation. These related to research to improve protocols, increase efficiency of conservation operations, increase security of conservation or address crop specific constraints for conservation such as seed dormancy, seed health, seed longevity, etc. Eleven institutions had no ongoing research, or it was only being seen as a future activity. Only 8-10 institutions have ongoing research in any of the areas identified. There were more institutions that considered these areas of research as important for their genebank in the future, especially to address specific constraints in their accessions, such as seed dormancy.

Figure 11. The number of institutions that have current or planned research into the various issues in conservation



Safety Duplication

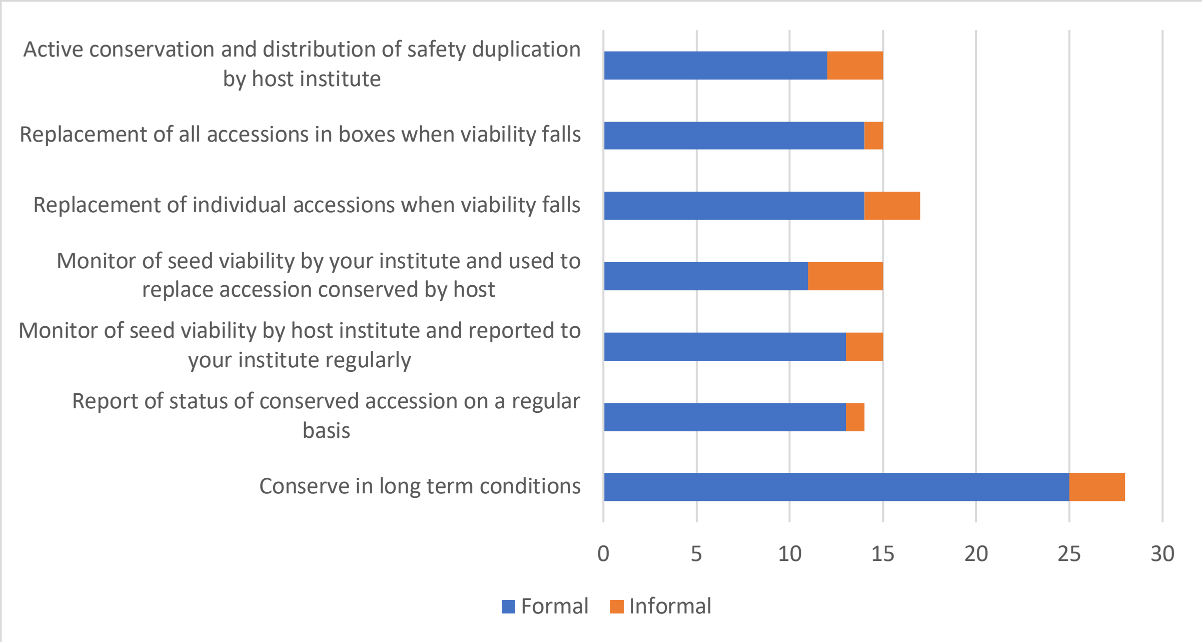
The international standards for safety duplication (FAO 2014) are that accessions that are original for a collection should be safety duplicated at a site that is geographically distant under conditions that are equal or better than the original genebank. Geographically distant is viewed as most distant if outside the country. The safety duplication should be done in a way that maintains the integrity of the original sample. When possible, this is best done through a black box arrangement where the accessions are only conserved by the host institution and the monitoring and replacement of low viability seed is done by the original institution. It is generally not seen as secure practice to have the accessions regenerated and managed actively by the host institution unless the risk to genetic integrity is managed and monitored. The survey asked the institutions to indicate the proportion of the accessions that were conserved in safety duplication sites. The sites were either Svalbard, an institution outside the country in a black box arrangement, an institution outside the country but dynamically managed by the host institution, in the same country at another institution, or in the same country but at another research site within the same institution. Only four of the institutes did not have their collection duplicated at any other site (Table 10). Fewer institutions had more than 50% of their collections duplicated at any other site but about one third of the institutes had some portion of their collection duplicated outside the country or in Svalbard. For the nine institutes that had safety duplication at one site, five were conserved outside the country.

Table 10. The number of institutes that conserved less or more than 50% of the accession in the various safety duplication sites

	Conserved in another research site in the country	Conserved in another collection in the country	Conserved at one site outside country	Conserved at least two sites outside the country	Conserved in Svalbard
Number of institutes with less than 50% of accessions conserved	4	4	10	5	12
Number of institutes with more than 50% of accessions conserved	7	4	5	2	1

Secure safety duplication also requires formal legal agreement that clearly state the terms and conditions for monitoring, conservation, and use. The survey identified several conditions that could be considered for safety duplication in a black box or in more active conservation for safety duplication. The institutions were to indicate if these were condition for their duplication sites and if this was a formal or informal arrangement. Nearly all the institutions had formal arrangement to conserve their duplicates in long term conditions (Figure 12). For the other terms and conditions, less than half had these kinds of arrangements for monitoring of viability and replacement of samples if needed. Most of these specified in formal agreements. In total, only 15 intuitions had safety duplicates that could be actively used by the host institution, and these were mainly based on formal agreement. The two institutions that had informal arrangement had their accession also conserved at another research site in the country.

Figure 12. The number of institutions that had formal or informal arrangements for the various terms and condition for monitoring, storage and use of safety duplications



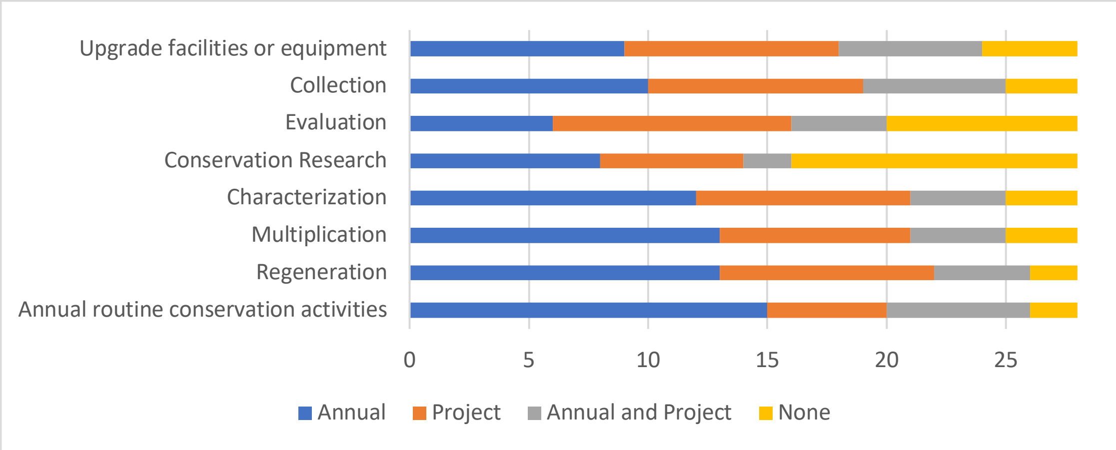
In 2007, eight of the 19 institutes had safety backups, but it was not clear what proportion of the accession were backup, the number of sites used, or the terms and conditions for these safety backups. It was clear in this update of the status that there was an increased awareness of the need for safety duplication and the institution intention to secure the collection better but there were significant constraints. Twelve of the institutions concluded they had no restriction to safety duplication, but the others indicated there were constraints related to national policy, phytosanitary requirements, and the cost to get permits, cost of packing and shipping, and the lack of funds for seed multiplication and processing to be able to safety duplicate the collection securely. This lack of adequate safety duplication for many of the accessions conserved globally is a key vulnerability that needs to be addressed in the future.

Human and Financial Resources

Staff number and level of expertise was adequate for most of the institutions for routine operations and meeting distribution requests. About one third of the respondents had inadequate staff training for information management. Several the institutes indicated they had inadequate number and level of staff due to lack of resources for positions, retirements, and poor retentions of staff. They mainly planned to address gaps with training and recruitment for new skills. Retention of trained staff was an issue for only a few of the institutions but mainly due to poor renumeration, the remote location of the genebank, and the lack of opportunities for new staff.

Most of the institution received funds from governments or international donors, including the Crop Trust. One institute indicated the genebank was supported from the breeding programs. The source of funds was considered separately for each routine operation and the upgrade of facilities/equipment in Figure 13. For about half of the institutions, annual funds were the main source of funds for routine conservation activities, regeneration, multiplication, and characterization. More of the institutions had annual and project funds for collection and the upgrade facilities and equipment. Evaluation and conservation research were two activities where the highest number of institutions had no funds currently allocated.

Figure 13. The proportion of respondents that had annual allocation, project funds, both annual and project funds or no funds for the various activities



The dependence of institutions on project funds for routine activities such as multiplication, characterization, evaluation, collection, and upgrades would indicate that there is less certainty of annual investment into enhancing use, securing genetic resources at risk, and securing conservation through adequate infrastructure and equipment just when needed. One approach to address this situation is through advocacy for more annual funds and safety duplication to ensure the security of the collection. The availability of a global competitive project fund to address urgent shortfall in routine funds and need for upgrades for collection holders of unique accessions also needs to be considered for the longer term as action for the global system.

Risk assessment

The identification of the risk for the collections, as well as developing a plan for mitigation that can be annually monitored is a key aspect of a quality management system. It is also a recommendation of the FAO (2014) international genebank standards. Nine institutions had risk assessment done and monitored by the Institution management or the genebank. The primary risk identified by the respondents were:

- Fire, drought, storms, theft, vandalism, and national calamities
- Security threat to genebanks, fields, and staff
- New constructions of roads and buildings in the area
- Uncertainty and irregularity in the supply of electrical energy required for low temperature storage and no investment into alternatives such as solar power
- Lack of secure and regular funding for long term conservation and collection management activities
- Uncertain and inadequate funds for staff and their training, equipment purchase, infrastructure construction, repair, and maintenance
- Inadequate and insufficient infrastructure to support routine operations and seed storage
- Inadequate safety duplication
- Insufficient resources for regeneration and multiplication
- Incomplete passport information and characterization data
- High grain moisture at harvest and loss of seed viability requires frequent regeneration that risk loss of genetic integrity or loss of accessions
- Lack of seed for distribution and in adequate storage facilities to hold enough seeds for distribution as well as inadequate packaging for storage and distribution.
- Inadequate representation of national diversity with replacement of landraces with improved varieties in farmer's fields
- Numerous disease and insect pest in field during regeneration/multiplication and post-harvest pest that impact on storage.

- The lack of pathologist or entomologist to identify and control pathogens and insect pest in the field, in seed storage and those transmitted by seeds.
- Mistakes and mix-up of seed with handwritten labels
- Large regeneration backlog that needs to be addressed initially with identification of duplicates for archival
- Low level of characterization to improve use and conservation
- Accessions are not accessible
- No back-up of genebank data
- No plans for upcoming staff succession

The impact of these risk was also evident when the institutions were asked to identify specific constraints they had for conservation of their collection. Some of the key constraints identified were the unknown redundancies with other collections; insufficient funds, expertise, facilities, equipment, and consumables for conservation, regeneration, characterization, distribution, and documentation; backlogs in regeneration and viability testing; insufficient staffing; accession identifiers not unique but changed over time; lack of safety duplication, no seed health monitoring; and no capacity to do genotyping. All of these are sources of vulnerability for the long-term conservation and use and needs to be considered for upgrading through global collaboration.

Summary of the status of conservation

When the status of conservation is compared with that reported in 2007, nine of the nineteen institutions had long term conservation, so storage was seen as a significant issue. They identified regeneration as a significant backlog for most of the institutions and recommended this be addressed urgently through global action. An effort was made to regenerate and safety back-up of the most critical collections with a project managed by the Crop Trust (Halewood et al 2020). This effort did result in securing some key collections and could account for the reduction in the backlog in the current assessment. It seems regeneration is still a backlog for many of the collections since globally, there are only about 50% of the accession that have been regenerated, especially for the wild relatives. There availability of regeneration guidelines for sorghum (Upadhyaya et al, 2008) is an important output from the 2007 Strategy as well. In the survey, 18 of the institutions were using these guidelines.

So generally, there has been an improvement in the conservation status for many of the 38 institutions in the survey that conserve 80% of the accessions. The global collections have fewer backlogs in routine operation than the national collections with inadequate facilities and equipment. The current global system is not secure, efficient, or rational with many gaps and vulnerabilities in key routine operations and facilities for some collection holders but not all. These gaps relate to knowledge on the viability and health of the conserved seed as well in management information. Globally, there is a gap in the regeneration of accessions and the multiplication of seed for distribution. The various collection holders in the survey had issues with the key facilities and equipment for the conservation and routine operations. There are also gaps in ensuring the use of the best and most efficient procedures and protocols through standard operating procedures, quality management systems, and conservation research. There is a need to consider the role of the global system to address these backlogs and upgrade needs for the national collections that conserve unique local diversity.

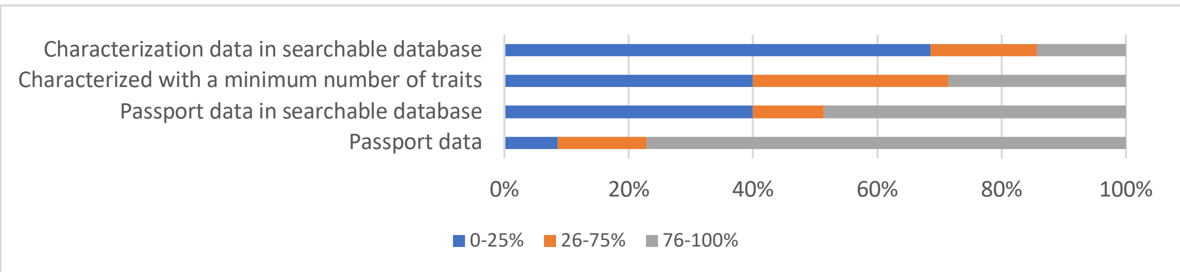
Status of *Ex Situ* collections –Documentation

In the 2007 strategy, they reported that the passport and characterization data was recorded and stored electronically at a reasonable but variable rate. They did not include any of the specific information from the survey to demonstrate the issues but in the 2021 survey, the institutions were asked to indicate the number of accessions that had passport and characterization data in a searchable database. FAO (2014) international genebank standards for documentation suggest that “passport data of 100 % of the accessions should be documented using FAO/Bioversity multi-crop passport descriptors" but the questionnaire did not address the issue of the use of FAO/Bioversity passport descriptors. The 2007 strategy did conclude that there was a need for genebanks to use standard taxonomy and nomenclature as well as to consider the utility of the characterization data. It also identified availability of the data online and its sharing were issues that needed to be addressed. They suggested three key actions for the future related to establishing a global information system that included the harmonization of the national collections, especially in terms of duplication, and to focus on the use of a minimum set of descriptors in a strengthened database. Some of these issues have been addressed through global actions, such as improved taxonomy and nomenclature in Dahlberg (2000) and Alercia (2011) describes the identification of minimum descriptors for characterization derived from IBPGR and ICRISAT (1993). The survey respondents were asked about their use of these publications as guidelines for their documentation. More than 80% utilized the IBPGR and ICRISAT (1993) descriptors but only 25% used the minimum descriptors reported in Alercia (2011). Only 4 institutions utilized Dahlberg (2000) as a guidance for the improved race classification.

As in 2007, the respondents to the survey were asked what type of data they had generally on the accessions and how it was made available to the users. Passport and characterization data were available on the accessions by more than 85% of the institutes. Images of the accessions were only available for 25% of the respondents. Accession level information from evaluation or genotyping were only available from seven of the respondents. Across the institutions, 95% of the accessions were documented in term of passport data and 85% is entered into a searchable database. Overall respondents and crops, 77% of the accessions had been characterized for minimal traits, while 69% of the accessions had the characterization data in a searchable database. So while the documentation of passport and characterization data has improved, in most of the institutions, the data was not publicly available, only internally (82%) and mainly in a catalogue or through the curator (75%). Less than 40% of the institutions shared the data online within the institute or more globally. While this is probably an improvement over the 2007 status, it is still an issue when you consider the availability now of global platforms like Genesys to share accession level information and genebank information system like GRIN-Global which facilitate sharing information online.

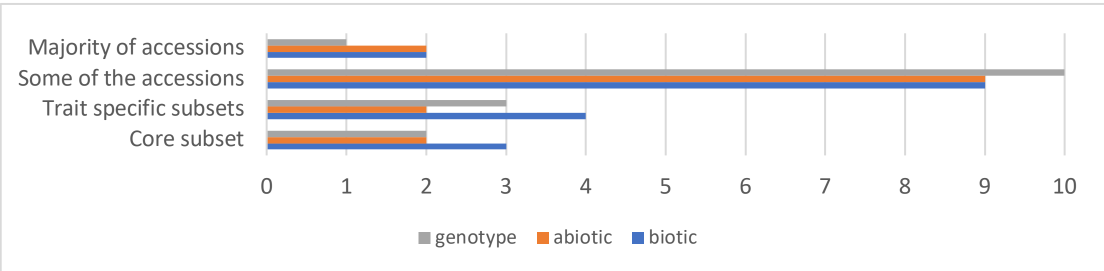
So while overall, there is a high proportion of the accession that have passport and characterization data in a searchable database, there is still a need for improvement when you consider the status within the institutions. There are very few institutions where there is less than 75% of the accessions are documented for passport data but for passport data in a searchable database, 40% of the institutions have less than 25% in a database (Figure 14). About 40% of the institutions had less than 25% of the accession characterized with a minimum number of traits and eight of these had no characterization data documented. The situation for entry into a searchable database where more than 70% of the institutions had less than 25% entered in a database and 21 of those had no characterization database. ICRISAT and USAD-ARS collections had more than 97% of their accessions passport and characterization data documented and shared online through Genesys.

Figure 14. The proportion of institutions that have 0-25%, 26-75%, 76-100% of accessions with passport data, passport data in a searchable database, or characterization data with a minimal number of traits, and characterization data in a searchable database.



The survey also requested information on the status of evaluation for the accession in the collection, both the traits that were evaluation, if they had been genotyped, and the use of core and trait specific subsets. There were 17 institution that indicated the accession had been at least partially evaluated phenotypically or genotypically. Nine to Ten of the institutions had at least some of the accessions evaluated (Figure 15). Only two instutions had the majority of the accessions evaluated for biotic and abiotic stresses and only one had been nearly fully genotyped. Core subset and trait specific subset had been designated and evaluated in less than 25% of the institutions that responded to the question. The lack of evaluation of collections and the sharing of the data was seen as a constraint for use in the 2007 strategy. There was recommendation that more use be made of cores and trait specific subsets. The current situation seems to be an improvement, especially for genotyping, but the respondents only represented less than 50% of the institutions in the survey. The biotic stress resistance was evaluated for downy mildew, grain mold, anthracnose, leaf blight, rust, elongated smut, gray spots and oval spots, stem borer, shoot fly, aphids, fall army worm, head bug, midge, striga, and abiotic stresses evaluated were water stress responses and low phosphorus tolerance. While some of the respondents shared characterization data with user there was only one institution that indicated they did not store the evaluation data generated by other but they did make links to it when it was available and they were informed. The 2007 Strategy had identified the development of a joint evaluation program as a priority for global collaboration, but this was never implemented. Thus, there is still room for improvement for the evaluation but also for the sharing of the data with users.

Figure 15 The number of institutions that have evaluated core subset, trait specific subsets, some of the accessions, and majority of accessions for biotic and abiotic stresses as well as genotyped.

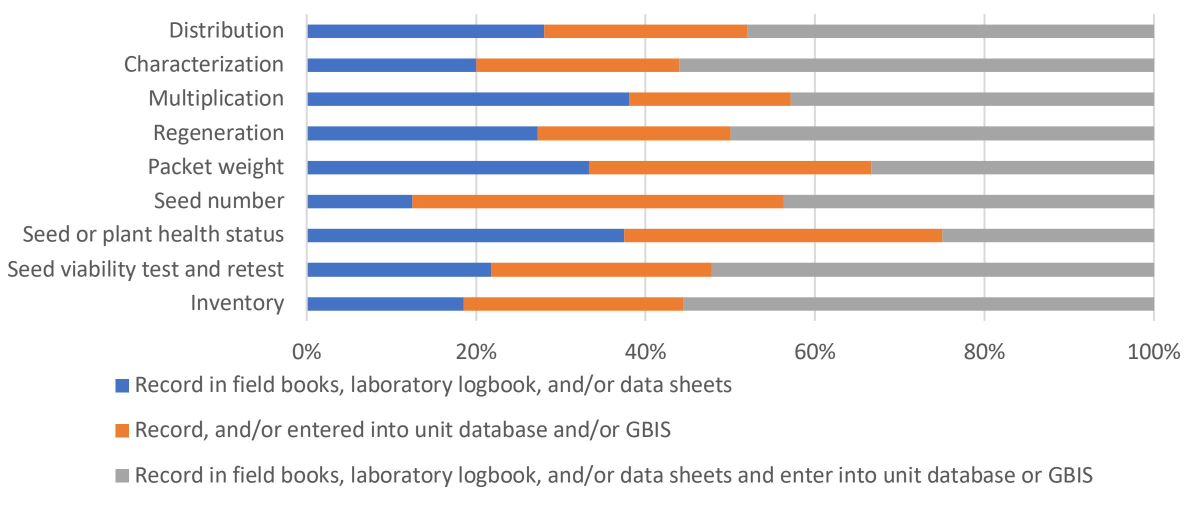


Hay and Sershen (2021) illustrated the critical data collection points in the flow of routine activities in genebank that ensure secure, efficient operations. They conclude that a robust information system is needed to capture all the data and track accessions in the process. Unfortunately investment into data management is not seen a key priority when resources are limited. Weise et al (2020) reviewed all the important information needs for a genebank. This included the specific needs for documentation and information for various operations or on accessions; the particular needs for staffing; the type of information to include in a genebank information system; the current option for an electronic information system, such as GRIN-Global, GBIS, MSExcell, and paper documentation; and the need for greater international collaboration for isses scuh as uniform data standards, exchange protocals and standardized documentstion. They concluded that the biggest challenges for the future will revolve around the collection, storage, and sharing of phenomics and genomics data. Both hay and Sershen (2021) and Weise et al (2020) concluded that the adoption of the currently available genebank information systems should facilitate capturing data from genebanks, sharing it with users and increase access to germplasm through online order systems.

FAO (2014) also has a standard for storage of all data generated in the genebank, both management and that associated with the accession. The recommendation is “All data and information generated in the genebank relating to all aspects of conservation and use of the material should be recorded in a suitably designed database.” Six of the institutes were adopting or are currently planning to adopt GRIN-Global while one institute is using the SESTO (https://sesto.nordgen.org/sesto/) based system, six also use the SPGRC-SDIS system and three institutes was using an institution developed system. There is increasing adoption and use of genebank management information systems but not all the institutes felt that their current system was adequate for the information needs.

To determine the extent of the use of a genebank information management system for conservation and information sharing with users, the survey asked questions about the approach being taken for data capture and use in a genebank information management system (GBMS). For some routine operations, such as inventory, seed viability test results, 100/1000 seed weight used for seed number determination, and characterization, there is less than 20% of the institutions that use only paper documentation (Figure 16). For some operations like seed health assessments, packet weight, and multiplication history, there are about 40% of the institutions that utilize only paper documentation. For nearly all the operations there is a significant proportion of the of the institutions initially capture the data on paper and then enter into the database. This approach can result in a delay in the use of the data since it is not a fully integrated system, but it can also add errors from transcribing a handwritten entry into the database. This does seem to be an issue for many of these institutes.

Figure 16 Proportion of institutions that record data generated from operation in field book, laboratory logbook, and/or datasheets; or record and/or enter into unit database or GBIS; or record in field book, laboratory logbook, and/or datasheets and then enter into unit database or GBIS for the various genebank operations



Adopting these information systems is a very important step to increasing the security and efficiency of conservation through better monitoring and reporting. To optimize these information systems requires a reconsideration of the processes and procedures used in the genebank. A barcoding system will reduce the risk of mislabeling and better protect the genetic integrity of the accessions. The adoption of electronic tablets for data capture directly into a database will also facilitate automation of some of the key tasks. In the survey, sixteen of the institutes were utilizing both barcoding and electronic tablets.

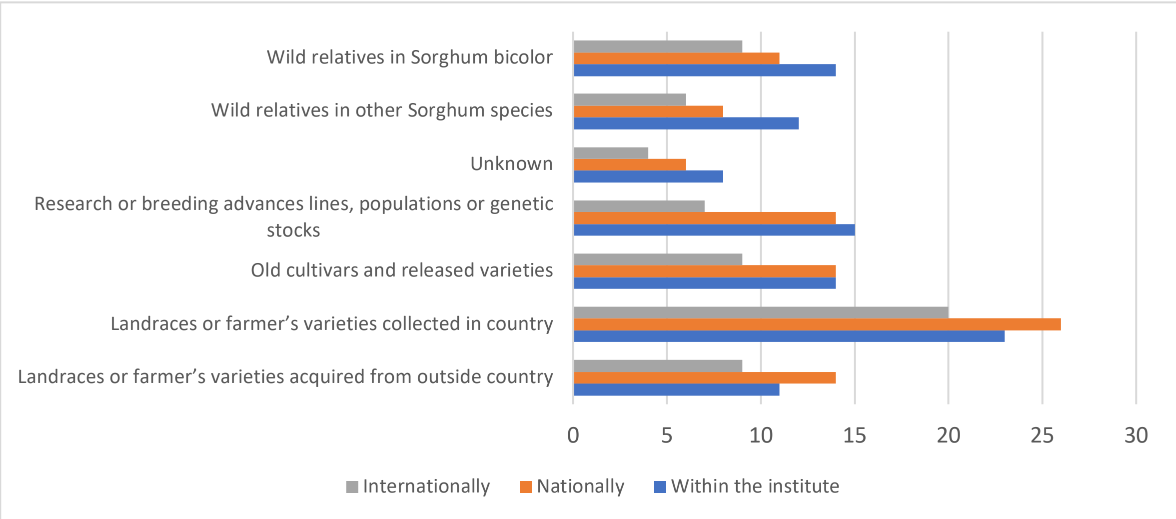
This effort to adopt a genebank information system by genebanks needs to continue and be supported since it will also lead to more opportunities to share accession level information as well through global platforms such as Genesys or on institute own websites or on both. Institutions that have fully adopted these GMIS should take the lead to facilitate the upgrade needed by other, mainly national genebanks. There is also a need to adopt a unique identifier, such as a DOI as described in Weise et al (2020), to allow for duplicates to be identified and links globally for rationalization if needed and to allow for a better assessment of gaps to facilitate collection development for both acquisition and collection. There is also a need emerging to better document of the origin of accessions as input into a complex system that is emerging to operate within access and benefit sharing policy implementation as reviewed by Brink and van Hintum (2020).

The adoption of a fully integrated GBMS that utilizes global sharing platforms such as Genesys should also increase the security of these databases since they can be safety duplicated on the cloud or in a separate server. No questions were asked about the security of these databases but that is an important aspect of a genebank information system that needs to be considered as well. The databases need to have safety back-ups frequently and one option for passport and characterization data is to upload them onto Genesys for back-up and sharing. The current accession level sharing platforms, such as Genesys, utilize a data sharing agreement with the contributors and these practices need to be considered more widely to allow for more user access to accession level information. The USDA-ARS in the USA and NARO in Japan have open, transparent sharing of a limited amount of the relevant passport data. These can be downloaded easily by the user to facilitate the selection of accessions. Globally, there is a need to increase the access by users to key accession level information to facility use.

Status of *Ex Situ* collections –Use

The survey requested information on the distribution of the accessions to various users in terms of the type of user, the frequency of distribution, the main use of the accession, any constraints to distribution or restriction to use, the exchange of accession level information, and any feedback mechanism with users. All but two of the institutes distributed to users within their institute and nationally and about 60% did distribution internationally with an SMTA or a government or institution mandated MTA. This is a similar result when the accession type is considered, most of the institutes distribute nationally and within the institute with few distributing internationally, especially for the accession without passport information, wild relatives in the other *Sorghum* species, and research products (Figure 17). Landraces that were collected form the country are distributed nationally and within the institutes by the highest number of intuitions. It would seem as if there were still constraints to the distribution of accession to users outside the country. Sorghum is listed in Annex I of the ITPGRFA so the use of the SMTA is common across the institutions that distribute internationally.

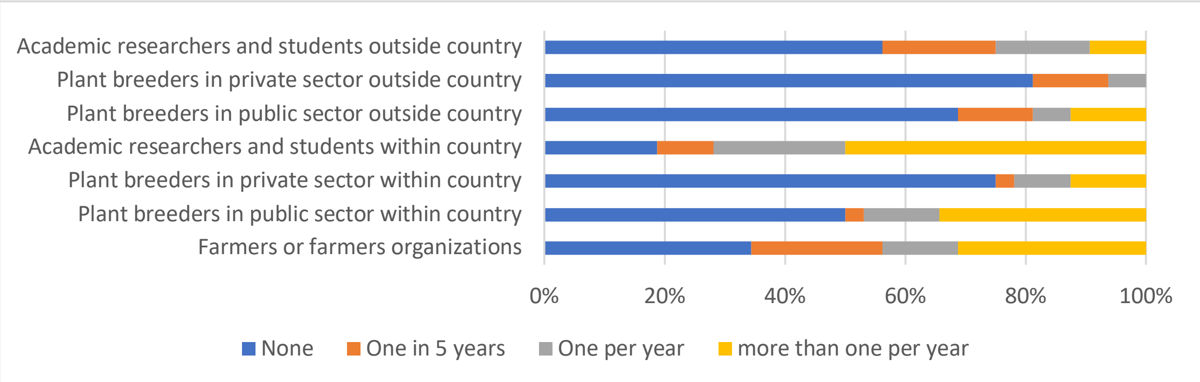
Figure 17. Number of institutions that distribution the various type of accessions internationally, nationally, or within the institute.



The distribution of accessions internationally (and sometimes nationally) requires an adequate procedure to be established for obtaining agreement to the terms and obligation through an SMTA or MTA, the issuance of the phytosanitary certificate that ensure the samples to be sent are free of the biotic threats or stressors for the importing country, appropriate packaging to secure and maintain the quality of the seed in transport, and the shipment through the appropriate route. The institutions were asked if they had adequate procedures and supplies to do distributions. Of the 27 responses, 24 had adequate processes in place to manage the SMTA and/or MTA. The main issue for two of institutes was the lack of national legislation to facilitate this process. Eighteen of the respondents indicated they had adequate processes to obtain the phytosanitary certificates. The main issues for those who were not able to obtain these certificates were due to cost or administrative challenge to obtain from authorities. The packaging and shipping of the seed was an issue for 10 of the respondents mainly due to challenge of getting the appropriate packaging material locally and that the procedures for shipping was inadequate due to the cost and the difficulty in meeting the regulations. These would be major constraint for international distribution.

The survey requested information on the frequency of distribution for seven user types separately. The most frequent distribution in the last five years was to users within the country, such as academic researchers and students, farmers and farmers organizations, and public plant breeders (Figure 18). A high proportion of the intuitions had done no distribution in at least the last five years to users outside the country or to the private sector within the country. There is likely a low investment into sorghum breeding within the countries and this might account for the lack of request, but it could also be an indication of a restriction to distribution to the private sector for a more commercial use. The lack of international distribution has been noted for many of the institution and this is also noted in the low frequency of distributions outside the country. The lack of accession level information being available for many of the institutions could also account for the low frequency of users outside the country also. The distribution of accessions at least once per year in the country for many of the institutions is a positive improvement over the 2007 survey. The high proportion of institutions that are distributing accession directly to farmers or farmers groups indicates that there is direct local use of the landrace accessions that could be important in the need for greater diversity in adaptation with the challenges from climate change.

Figure 18. The proportion of institutions that had no distribution or at least not in the last five years, or a distribution at least once during the previous five years, or one distribution per year, or more than one distribution per year for each user type separately.



Finally, the survey requested information on any feedback solicited on the quality and use of the accessions received. All institutions solicited feedback from recipients but only nine of these used a formal process. The most frequently feedback requested was on the quality of the samples dispatched, the usefulness of the accession received, sharing of reports or publications, and sharing of characterization or evaluation data sets (Table 11). Very few of the respondents solicited feedback on the quality of the packaging used. Those that used a formal process mainly used a survey sent after the distribution. The use of this feedback was described by one institution as “feedback was used to improve the quality of seed, information on accessions, and efficiency of operations as well as to track use of accessions sent. It allowed for the opportunity to incorporate additional characterization or evaluation data that was shared. It was used to be able to report or communicate on use of the accessions distributed or the value of collections. The collation of research publications was used to enhance future research by sharing research results derived from the germplasm distributed." This view was shared by a number of other institutions.

Table 11. The number of respondents that solicited the specific area for feedback or follow-up with recipients of the accession

Specific areas for feedback from users on:	Number of respondents
Timeliness of the distribution	10
Helpfulness of information or advice from genebank staff in selection of accessions	10
Quality of samples sent	11
Quality of packaging used	6
Quality and the usefulness of the accession level information received	9
Usefulness of the accession received	17
Sharing of report or publication on any specific research result from the evaluation or use of the accession received	19
Sharing of evaluation or characterization data sets	15
Variety releases, adoption studies or case studies from the use of an accession received	9

Generally, the status of distribution for sorghum genetic resources was more focused within the institution or nationally. International distribution was a challenged by policy, cost for distribution, and complex administrative constraints. The main users of the sorghum collections were nationally based researchers and breeders as well as farmers. The lack of private sector breeding programs has limited the uses for these collections. Soliciting feedback from recipients should be formalized to enhance its use to improve quality of seed and services, better understand the user interest in accessions, and to communicate the value of the accessions and the collection more widely.

Status of *Ex Situ* collections –Links to users

The links of *ex situ* collection holders to each other and to various types of users is critical to secure the long-term conservation as well as to ensure its long-term use. The survey explored the degree and diversity of these interactions by considering the types of activities and the types of partnership the collection holders had experienced for conservation as well as use. As reported in Table 12, the most frequent partnership was with other national collection holders (19 out of 23 responses) and regional/international collection holders (14 out of 23 responses). The least frequent partnership was with protected sites for wild species where only 4 of the institutions had engaged. The main activities that the institutions participated overall was research and training but there were specific activities and partners, such as seed multiplication with regional/international collection holder, where all 14 institutions had experience. Collection was also an activity that was done jointly by more than half of the institutions that engaged with other national collection holders, community seed banks and on farm conservation sites. Ten of the institutes indicated that they had received additional support to be part of the activity. When asked if these joint activities were increasing or decreasing, 16 respondents indicated they were increasing for some or all the various types of partners. These results indicate that there is a fairly significant degree of interaction between conservers in the current global system that was was focused on national or local level partnerships to collect, conserve, and enhance the use of sorghum genetic resources. For the future, the level of interaction with more locally focused conservers is an area that needs to be strengthened as in many areas of Africa and Asia sorghum landraces or farmers varieties are still mainly conserved by local farmers on the farm or in community seedbanks. The number of institutions with links to *in situ* conservation site and protected sites for the wild relatives were less and this is a risk for the wild relatives that are under threat in these sites. This link is also an opportunity to enhance the partnership of experts on conservation with experts on crop diversity.

Table 12. The number of institutions that have been involved with various other conservers internationally, nationally, or locally for collection, repatriation, research, training, seed multiplication, demonstration, and field days

	Collection	Repatriation	Research	Training	Seed multiplication	Total number of institutions
Regional or international ex situ collection holders	7	7	8	11	14	14
National ex situ collection holders	7	4	8	7	5	19
Community seed banks	5	2	4	7	3	7
In situ conservation sites	2	2	1	4	3	7
On farm conservation sites	5	2	2	5	3	9
Protected sites for wild relatives			2	2	1	4

The survey also explored the links and level of activities between collection holders and various types of users. Twenty-seven institutions reported on their experience in partnership with the various users given in Table 13. The most frequent partnership was with local users (22/27) and national researchers and breeders (23/27). Local users included farmers, farmer organizations, NGO's, and the extension service. The least frequent partnership were with the private sector but again that could be due to the low level of investment into the seed sector for sorghum. With the local users, the most frequent joint activity was with demonstration and training. With the research users such as the national and international researcher/breeders, academic researchers and private sector breeder, the most frequent joint activity was research. Joint activities that involve field testing and promotion as well as training were undertaken by a number of these institutions with the various partners The level of activity for the institution in the survey was broad and demonstrated a significant level of engagement with users at all levels in the current global system. These partnership and experience can be built upon for the future given there are many experiences to share to enhance use. About 50% of the institution indicated that got some additional support for their involvement in some or all the activities. Overall, 16 of the institutions indicated the level of activities with the various researchers were increasing.

Table 13. The number of institutions that have engaged with local users, national researchers and breeders, international researchers and breeders, university faculty and students, and private seed companies for the various activities.

	Local users	National researchers and breeders	International researchers and breeders	University faculty and students	Private seed companies
Repatriation	4	5	3		
Seed multiplication	9	13	4	3	2
Participatory evaluation	8	12	4	2	4

Demonstrations	13	13	3	4	5
Field days	8	11	4	5	4
Research	5	22	9	17	5
Training	11	11	4	8	1
Seed fairs	1	1			1
Collection		3	1	2	
Total number of institutions	22	23	11	18	7

Overall, direct engagement of the collection holders with these local users is very encouraging for sorghum. Sorghum landraces or farmers varieties are still mainly grown by local farmers for their own or local consumption. Thus, the collection holder's engagement with the local farmers, directly or indirectly, increase opportunity to share the accession conserved as well as collect and conserve more of the germplasm that is still held by these farmers. This is an opportunity to both secure the genetic resource that are under threat from genetic erosion or loss in the field but also contribute to adaptation to climate changes, rural development, and food security.

While there is active engagement of the ex situ collections with each other, the research community, and the local farmers or communities, there are very few networks or collaborative initiatives that engage the respondents globally, across crops or within each crop. ICRISAT, as CGIAR Center with an international collection, has taken the lead on actively engaging with partners for the crops they conserve and IRD continue to engage with the countries. There are more regional networks such as the SADC Plant Genetic Resources Center (SPGRC) that involve all the collection holders for sorghum in the SADC Countries. There is also the European Cooperative Programme for Plant Genetic Resources (ECPGR) for European collection holders. Unfortunately for sorghum genetic resources, there are few international platforms for collaboration, except for a few project specific sequencing and genotyping effort that have involved global coalitions. This was recognized as a constraint in the 2007 strategy and the suggested action included enhanced global sharing of accession level information and strengthening the links between genetic resources program or the genebanks with researchers/breeders for evaluation and pre-breeding.

Status of *Ex Situ* collections -Constraints and vulnerabilities

In the previous sections, there have been concerns identified in relation to priority needs to fill gaps in conservation of genetic diversity in collections; secure, efficient routine operations; sufficient genebank facilities and equipment; accessibility of users to accession level information; user engagement; and partnership opportunities. All of these are sources of risk for the long-term conservation and use for individual genebanks as well as for the global conservation system. There could be additional risk due to inadequacy in staffing, poor planning for staff succession, inconsistent financial support, and lack of attention to management and mitigation of risk by the genebank.

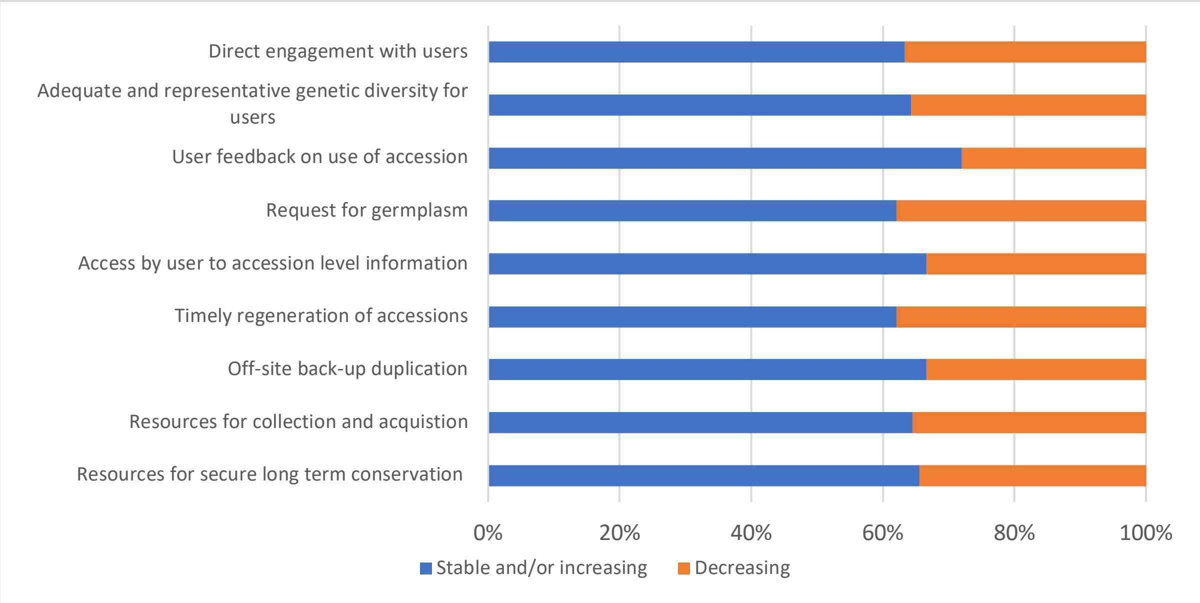
The institutes were also asked to identify the key constraints they had for the use of their collections. The areas identified were:

- Sorghum was not a national priority so there was a lack of resources for research and development that limited the use of the collections
- Sorghum was also not seen as a priority for commercialization through new uses so investment into the crop and into the seed production limited use by the private sector
- Weak links between breeding programs national, regionally and internationally limited information sharing on genetic resources
- Insufficient accession level information that could be useful to users and no sharing of the information
- Lack of funds for evaluation in the genebank and with the users

- Lack of sufficient investment into integrating phenotyping and genomics to link traits and alleles to use, especially for the whole collections
- Insufficient quantity and quality of seed for distribution as well as the cost and administrative burden for distribution.
- Quantity of seed sent to users to small
- Evaluation traits need to be systematically assessed in the whole collection, including nutritional profiling.
- Unclear, complex process for assess germplasm
- No funds for promotion of germplasm with demonstration and other activities
- No funds for genotyping
- Lack of awareness of genebank and the conserved germplasm
- Lack of a clear strategy for conservation and use of the collection

Finally, the survey requested feedback from the institutions on the overall status of their collection in relation to key issues for the future conservation and use. There were 35 responses to these questions. Most of these were considered as areas for improvement in the 2007 strategy. For all these issues, less than 40% of the intuitions considered the status as decreasing (Figure 19). Thus, for the key issues for conservation such as resources for long term conservation, collection expansion, timely regeneration, safety duplication, accession level information sharing, and use were at least stable. It was also encouraging that such a high proportion of the institutions considered they had stable or improving engagement with users with a collection that had adequate genetic diversity and accession level information to meet the needs of users. There was increased or stable request for accessions and feedback from user on their use. All these are very positive in relation to the future for conservation and use but the decreasing status is still a concern and would indicate a need for greater collaboration to secure these collections.

Figure 19. Proportion of intuitions that have a stable and/or increasing status or a decreasing status for the various issues for conservation and use in the future. (n=35)



The institutions were also asked to describe some specific contributions that their collections will make to the global system. Many of these related to the security of their conservation, the availability and accessibility of the accession to users, the high level of local diversity that was conserved, the important of their collection to local farmers and researchers, and the specific traits of accession they conserved. Here are some of the responses:

- Secure conservation of diverse germplasm that is accessible for research purposes

- Ease of use so accessions are available, being evaluated and used for breeding new varieties
- A large number of accessions from the country are accessible through other genebanks where they are also conserved, distributed, and often used in research
- Unique local landraces with traits such as scented sorghum, high protein lines, drought tolerant lines, shoot fly resistant lines, resistant to leafy disease, early flowering and early maturing, high grain yielding, High biomass lines, High brix lines, striga and midge resistant lines, stay green, and salinity tolerant
- Facilitates the opportunity for safety duplication of sorghum accessions at Svalbard Vault and at other genebanks, like ICRISAT
- Accessions have been exchanged within the East African countries in one of the projects called the open source seed system in which farmers were able to select preferred varieties for adoption into their farming systems.
- Accession have been used to restore lost varieties to farmers and breeding programs
- Protection of landraces which have disappeared among local farmers (for example long duration accessions)
- Nationally, ensure diversity of land races from different agro-ecological zones are conserved for the future that could be utilized by farmers or for crop improvement programme.
- The collection conserves a great variability of sorghum both morphologically, physiologically and certainly genetically that will enrich the global collection and its accessibility will be easier for various improvement programs around the world.
- Crop wild relatives collected and available via SMTA.
- Unique accessions of Australian indigenous crop wild relatives in the tertiary genepool. Many of these species are not represented in any other global collection. Active collecting program to collect and conserve gaps in Australian indigenous CWR species.
- Agro-morphological characterization activities have been implemented and data available for use of relevant accessions for further activities mainly by breeding programs.
- National collections with rich unexplored and highly underutilized germplasm offer an opportunity for exploration for key traits for drought, pest resistance and other desirable attributes. Some of that diversity is still being actively managed on farm by farmers and the key traits have been observed from among the local landraces.
- Regional collection from different SADC Member States with a breadth variety of diversity the is securely conserved.

Each institute was also asked to identify some key advantages for their collections conservation and use from participation in a global conservation system. There were a number of benefits from global collaboration that were described that related to access to funds for upgrades in facilities, equipment, capacity, and routine operations to secure the conservation for their collection. They also identified the opportunities for safety duplication with other genebanks, greater sharing of accession level information, and increased access to accessions. Some of the specific advantages that were identified were:

- Information about global status of sorghum collection, diversity, conservation strategy and recommendations will strengthen collection and use globally.
- Opportunities to identify and fill gaps in collections for landraces, wild relative, and improved varieties, and research material
- Secure the conservation and enhance use of national collection of locally adapted landraces
- Access to latest working protocols for improving routine operations
- Upgrade routine operations to ensure long term viability with reduced risk of genetic erosion for unique accessions and clear guidelines for access

- Greater opportunities for international collaborations and access to resources to improve management and enhance use.
- Providing sharing of passport data of sorghum collection through GRIN-Global and Genesys.
- Safety duplication in back-up sites with other genebanks and in Svalbard.
- Exchange of genetic material which serves as source of variability for new breeding objectives.
- Exchange of scientific techniques in breeding and phenotyping
- Resources to collect, conserve, characterize, and use local landraces
- Make use of collections to safeguard global food security and contribute to global plant conservation and crop breeding initiatives.
- Benefit from funding, training, and equipment to better manage and enhance use of our plant genetic resources
- Existence of stations equipped with an irrigation system to facilitate the multiplication of plant genetic resources for the region
- Facilitate evaluation programmes across sorghum growing countries to identify trait specific germplasm and make available
- Access to the diversity from international collections to support National sorghum research and breeding programs.
- Secure the conservation of the collection to reduce regenerations that risk loss of diversity.
- Resources for the establishment of a genebank information system that is accessible to curator as well as users
- Opportunity for sharing services, facilities, and collective capacity building in collection management
- Enhanced availability to the interested users both nationally and internationally with clear term and conditions for accessibility

Finally, one of the national genebanks described the advantage as “Participating in a global conservation system will enable me to realize critical gaps and areas of improvement in long-term conservation of sorghum accessions for the benefit of current and future generations. It will shed more light on possible funding agencies to enhance genetic diversity of the sorghum collections. This will also increase global recognition, as it is currently not widely known, resulting in more requests of the conserved sorghum accessions, and subsequently more benefits to be realized.” Thus, there was a broad consensus amongst the survey respondents that global collective actions would benefit their collection and their collection would make specific significant contributions to this global effort.

Sorghum User Community Consultation

Over the past 15 years significant national and global investment has been made in generating genomic resources to advance breeding and conservation activities. In 2004, members of the worldwide sorghum (Sorghum spp.) community, including private sector and international scientists as well as community representatives from closely related crops such as sugarcane (Saccharum spp.) and maize (Zea mays), met to lay the groundwork for future advances in sorghum genomics and to coordinate plans for sequencing of the sorghum genome (Kresovich et al. 2005). Key developments that made this workshop timely included advances in knowledge of the sorghum genome that provide for the development of a genetically anchored physical map to guide sequence assembly and annotation, the growing role of the sorghum genome as a nucleation point for comparative genomics of diverse tropical grasses including many leading crops, the size and simplicity of the sorghum genome, and the need for dramatically increased sorghum production to sustain human populations in many regions where its inherent abiotic stress tolerance makes it an essential staple. In 2009, the first assembled and annotated sorghum genome was completed (Paterson et al. 2009) and this major effort provided the foundation for an explosion in the development of valuable resources for sorghum genetics and breeding. For recent updates on the current status of available sorghum genomic resources, see Boyles et al. 2019; Mace et al. 2019; and Hao et al. 2021. In addition to providing valuable insights, tools, technologies, and methods for sorghum improvement, these resources have also proven useful to advance sorghum conservation and to link conservation and utilization.

Recognizing this unique and opportunistic position of sorghum genomics globally, when the current sorghum conservation strategy was undertaken, a concurrent activity was conducted to establish a complementary viewpoint from stakeholders (rather than curators) to determine how genomic resources are and could be used to improve conservation efforts and enhance utilization of genetic resources

An expert consultation for "Securing the Long-Term Conservation and Use of Sorghum Genetic Resources Globally" was held on 23 September 2021. The goal of the session was to bring together global experts (with particular insights in genomics, bioinformatics, conservation, gene and trait discovery, phenomics, breeding informatics and statistics, and pre-breeding) to provide their complementary recommendations regarding conservation activities from a user perspective to those generated previously by curators of global sorghum collections. The half-day session was attended by approximately 25 investigators from research programs around the world. The agenda of the meeting and attendees are provided in Appendix IV of this report.

From a stakeholder's viewpoint, the metrics of a "good" collection include: (1) the holdings represent key genetic and phenotypic diversity of the species and its wild and weedy relatives; (2) good characterization and evaluation of the of the materials; (3) availability of the information from collection through evaluation; and (4) availability of high-quality seed and/or other propagules. With these standards, the following points highlight key action items proposed and/or recommended.

- There is an explosion of genomic and phenotypic data generation, and data curation is a concern. Curators need to be aware of scientific advances. However, there was consensus among participants that curation would be best done by those generating the data.
- When possible, gene bank curators need to establish closer ties with appropriate global genotyping and phenotyping networks. Gene banks should integrate key, proven technologies to improve characterization and evaluation of holdings.
- While molecular techniques may play a useful role in characterizing diversity, many technologies lack the ability to identify novel variation among accessions. However, future advances in DNA sequencing will improve discovery capabilities.
- There needs to be improvement in interoperability between databases that store genetic and phenotypic data and the gene bank information for ex situ genetic resources. Some efforts are underway to link DOI of publications with their germplasm source.
- While there is clearly some need to address redundancies among collections, the long-term cost of maintaining those holdings is low compared to the cost of addressing the problem.
- Gap analysis and more coordinated strategies for assessing diversity across gene banks and national collections are necessary to enhance conservation of in situ diversity and its use.
- Additional funding will be critical to link gene bank and their users for advances in breeding and genetics. For example, a "win-win" opportunity could be created by providing support to gene banks for pre-breeding activities that integrate useful genetic and phenotypic variation into more agronomically relevant backgrounds for ready use by stakeholders.
- Crop-specific curators, with improved training in genetics and breeding, will be required as collections develop in size and complexity. For example, many

collections now accept genetic stocks and extensive genetic resources (e.g., nested association mapping populations) in addition to classical accessions. Therefore, effective genetic management of holdings is essential.
- New tools, such as gene editing, might enhance and expedite the use of germplasm diversity if gene bank collections are more aggressively employed for allele mining.

Global Strategy for the *Ex Situ* Conservation of Sorghum Crop Genetic Resources

Sorghum is an important cereal crop for trade internationally and for food security in many localities in the tropics where traditional production is in environments that are marginal and dependent upon increasing erratic rainfall and higher temperature with changes in the climate. In the more temperate regions, there is a decline in production that is related to reduced traditional use and low market value due to limited commercialization since there are more profitable alternative cereal grains or fodder. These shifts in the importance of the crop is a risk for loss of conserved genetic resources that are in ex situ collections in countries where sorghum is seeing a decline in investment into research and development. In the tropics, the production of sorghum has increased with a shift to more marginal areas where it is an important food and feed security crop in environments challenged significantly by climate change. The challenges of climate change in the traditional production areas could be a risk for loss of diversity in farmer's fields and natural areas for the crop wild relatives. It is also a challenge for farmers to adapt given the poor productivity of the crop in Africa and the lack of investment into sorghum research and development in these areas. Thus, the production of sorghum globally is clearly vulnerable, and it is facing many constraints that will depend on the use of the genetic diversity that is conserved for the future.

The current global system for conservation and uses consist of:

- Local farmers and households who conserve and manage most of the cultivated crop diversity
- Natural areas where most of the diversity of the wild relatives are still conserved
- Three international, one regional genebank, and 11 national genebanks that conserve mainly accessions from other geographical origins
- National collections in the center of diversity that conserves a high proportion of local diversity but have greater opportunities for local engagement with users for conservation and use
- National collections that are located outside the center of diversity that conserve accessions that are likely duplicates of those held by others or locally adapted with unique traits, but their support is national and as national priorities change, they face an uncertain future for conservation and use.

The current global system of conservation and use is not meeting international standards for many of the collection holders and is generally insecure, with inefficient and poorly resourced operations for many national institutions, limited availability of seed to all users, limited sharing of accession level information with users, and limited engagement of conservers and users globally, nationally, and locally. This is not the sustainable, rational, secure, and cost-effective system that is needed for long term conservation and use of sorghum genetic resources to meet the challenge of the future. Some of this is due to the low priority given to sorghum by international donors, national governments, public and private researchers, local authorities, local farmers, local and urban markets, and consumers. This decline in priority is not only a risk to ex situ conservation but also to the continued conservation of diversity in farmers' fields and in natural areas. The 2007 strategy highlighted the key elements of an effective and efficient global conservation system. These elements are still relevant today and the need for global collaboration is still a priority to take the needed actions to secure conservation and enhance use.

The current global conservation system does have some advantages that can be built upon. For example, it has genebanks that can be turned to for expertise and guidance in the effort of other conservers to meet international standards. These genebanks can also serve as conveners in any global effort to increase security of conservation, adopt new technology and methods, enhance capacity and expertise, and collectively address some of the major constraints to the shift to a more efficient, sustainable global system. These genebanks could also take on leadership in the advocacy and communications on the importance of conservation and use of diversity with much of the focus on what is being done more nationally and locally by other conservers in the system. There are other advantages in the current system related to the national and local nature of conservation where value added research and development can directly utilize local germplasm with the involvement of local farmers and consumers.

One of the main disadvantages of the current system is the lack of committed annual support for conservation of these crops in many of the national genebanks, the general lack of knowledge of the diversity that is duplicated and conserved, the low level of support for research on sorghum, and the vulnerability of much of the diversity to loss, both ex situ in genebanks as well as in farmer's fields or in natural areas. The purpose of this strategy is to recommend priority actions to shift from the current system to a more coordinated and informed global conservation and use system that is more secure, rational, cost-effective, and engaged with user. These recommended actions will be used by the Crop Trust and others to identify key investments needed to secure conservation and use for long term.

The strategy developed in 2007 included experts who made commitment to engage in the agreed priority actions on Task Forces. This firm plan seemed to be what was needed to take at least the first step to a more global system. In 2021, the need for action globally is just as urgent but there has been significant progress at the individual genebank level and in the establishment of a global information system to share accession level information. This has not increased use though, even with the increased availability of core and trait specific subsets from some of the key collections. The consultation with the user highlighted the important of ex situ collections to the users but their standards for a 'good' collection differs from that of the curators with much greater focus on availability and facilitated access to accessions and to accession level information that relates to potential use. The key action areas for global collaboration identified by the users will challenge the conservers to reconsider the information shared, the type of germplasm conserved, the application of genomics, phenomics, and informatics in a genebank to facilitate the discovery and use of allelic diversity, and the need to take on a greater role as a bridge to facilitate prebreeding. Many of the future needs could be addressed by individual actions or even limited collaboration between genebanks and users as has been done so far but it is likely to still be insufficient to address the vulnerability of a high proportion of the genetic diversity for sorghum and its wild relatives. There seems to be a high recognition of the value of a global system but that will require commitment by individual genebanks and scientists to collective actions that are long term. The issue is not what needs to be done, that was clear in 2007 and is clear now, but how do we take the needed actions and sustain the gains made for long secure conservation given the vulnerability of the current conservation and the future demands for genetic diversity in sorghum.

A global strategy requires the identification of key priority actions that need to be taken, who should be involved, and what kind of financial support will be required to complete the required tasks. Three strategic initiatives are identified from the survey along with the key actions required:

1. Securing conservation of sorghum genetic resources for the long term,
    a. Address insecurity in ex situ conservation due to sub-optimal routine operations, facilities, and safety duplication for key national genebanks

   b. Address the need to identify duplication across genebanks and gaps in conservation of unique diversity in ex situ as well as still being conserved in farmers field and in natural area
   c. Address needs to conserve research material
   d. Address constraints to global engagement of conservers and conservers with users
   e. Advocate and communicate on the importance of the crops and its conservation to the public, local governments and communities, policy makers, other research communities to increase awareness and financial support
2. Increase the availability and exchange of germplasm
   a. Address constraints to distribution from insufficient seed quantity, quality, and viability
   b. Address administrative, technical and policy bottlenecks to distribution
3. Increase the use of the conserved genetic diversity.
   a. Increase the access to accession level information that meets the needs of users, preferably online to all users
   b. Increase evaluation (via phenomics) and genotyping with users to facilitate use
   c. Continue to establish and make available core collection or other subsets to facilitate discovery and use of valuable traits
   d. Increase research community users and farmer engagement with genebanks

Implementing the key actions in these three strategic initiatives will facilitate a sustained, longer term, rational global conservation and use system. The 2007 global strategy for sorghum as well as this strategy in 2021 have identified priority needs to be addressed. The primary focus for collaboration in 2007 were actions that would increase the availability of accession level information to address redundancies and to better meet the needs of the users. Little action was taken globally since 2007. Amongst the global genebanks, individual genebanks have taken some of the actions to improve the conservation and use of their collections. To take the key actions required in the three strategic initiatives will require committed leadership to find and facilitate the use of dedicated financial resources to implement these actions, both from increased annual allocations as well as more targeted specific funds. Thus, taking lessons from the previous strategy, two priority actions have been identified for the initial implementation of the strategy.

Priority Action 1: Global initiative to address redundancies and fill global gaps in conservation

As in 2007, elite materials and landraces are still the prominent types of accessions conserved and the wild relatives are still a significant gap in conservation. There is evidence of significant redundancies across collections that needs to be assessed as recommended in 2007. There are benefits from global action to explore this duplication to enhance security and use of the diversity. There are also significant gaps in the conservation of unique local accession from certain countries, in farmer’s fields in specific localities, and in natural areas for the wild species. Thus, the top priority action for global collaboration is a global initiative to identify and minimize redundancies and fill global gaps in conservation of sorghum genetic resources. There are four important activities that needed to be taken in this global initiative.

The 2007 strategy recognized that the top priority for global collaboration was the development of a global information system for sorghum genetic resources as the first step to strengthen the global system. The global information system would allow for the identification of duplicates with globally agreed unique identifier for accessions. A global platform for sharing accession level information across crops is now available with Genesys. The publication of data from USDA-ARS, ICRISAT, AGG in Australia, and the European collections on Genesys has resulted in much greater sharing of accession level information.

Individual genebanks that hold duplicates might consider the option of archival collections as described in Engels and Ebert (2021b). The identification of duplicates and unique entries between ICRISAT and the USDA-ARS collections was a priority for 2007 that unfortunately was not addressed. **The first action for this global initiative would be to proceed with the assessment of redundancies for the institutions that account for a high proportion of the accessions globally.**

The lack of complete accession level passport data being available and shared will be a constraint to the identification of the gaps globally but the high degree of duplication for accessions from some countries could be an initial focus for action. There is still very limited availability and access of accession level information to user through online, searchable platforms from most of the institutions in the survey. Much of the genebank information and accession level information is still not digitized or only within internal databases. There is a need for wider adoption of genebank information systems, like GRIN-Global or others will increase monitoring and efficiency of management of conservation but will easily allow for more online sharing of the accession level information. It will also allow for better back-up of holdings and documentation. This will also allow for greater linking of collections within the global system to enhance use and better secure conservation. **Thus, a key activity of this initiative will be to upgrade the information systems in priority national collections and ensure the sharing of at least complete passport and related data into Genesys.** The increased availability of accession level information will benefit the assessment of duplication initially and will support the global gap analysis that needs to be done. There is also a need to address policy constraints with the sharing of accession level data with data sharing agreements. Investment into upgrades will need to be initially targeted to those institutions that are able to share the data with Genesys.

The identification and quantification of duplication and gaps will be enhanced with the use of allelic level measures of gene and genotypic diversity that will be possible with greater application of genomic tools, technologies, and methods (TTMs). This activity will require greater sharing of accession level genomic information as well as the coordinated use of facilities and expertise to allow for a more comprehensive assessment of diversity across collections. **The activity to enhance the use of allelic diversity will require investments into genotyping (and ultimately phenotyping) but initial step will be the establishment of working group with a focus on the planning and guidance for this action will be critical for its implementation since there will need to be a consideration of the appropriate TTMs, the collation and sharing and long-term storage of the data, the global agricultural targets for genotyping, and the analysis of the results that will be needed to enhance its application to this effort.**

It that clear that global collaboration is needed to both assess duplication and identify the priority gaps of traits and accessions that need to be secured through collection, on farm conservation or in situ conservation in protected areas. With greater sharing of complete passport information on accessions through Genesys, it will enable the global assessment of gaps that is needed to secure unique gene and genotypic diversity that is at risk of loss. Moreover, the gap assessment needs to consider cultural and social influences on distribution of diversity and the utilization of genomic TTMs to incorporate allelic diversity measures of uniqueness and potential value. There have been numerous approaches taken to identify gaps in the past and **this activity in the global initiative needs to convene a broad range of experts and users to agree upon the goals and approach to take globally. The approach then will be implemented to identify global gaps that will be addressed with investment into collection and other activities to secure the conservation.** This action would serve to expand links and activities of *ex situ* collections with on farm conservation sites, community seedbanks, *in situ* and protected sites to secure the global diversity for sorghum and their wild relatives that harbor significant gaps currently. Another action required to address global gaps is to invest into a global conservation planning exercise to determine key priority sites that would need to be targeted for detailed *in situ* conservation interventions.

The lack of response from collection holders in Europe, China, Japan and other areas where sorghum production is in decline is worrisome. Many of the collection curators that did not respond represented small diverse collections or specialist collections. They are likely to maintain some unique germplasm that could be at risk of loss if priorities for research and development in the country and institute change. This gap needs to be addressed and these collections engaged more fully in the global system through this global initiative. One key function for the global system needs to be its ability to respond to risk of loss of diversity in ex situ collections. The ability to monitor the status of conservation for unique accessions in individual collections will be enhance with greater sharing of accession level information and the partnerships strengthened through this global initiative. It would also facilitate the establishment of an early warning monitoring system for tracking the loss of sorghum genetic diversity from farmer's field and in the wild. These are all high priority information needs to secure sorghum genetic diversity globally.

Priority Action 2: Global initiative to secure conservation and use of collections for the future users

Generally, global genebanks meet the internationally recommended standards for conservation of orthodox seed to a greater degree than the national collections. Many national genebanks in the centers of diversity have limitations related to inadequate facilities, equipment, staffing, regeneration sites, and funding. This is leading to dangerous backlogs in viability testing, backlog, regenerations, and multiplication that is a risk for long term conservation and has limited the quantity and quality of seed available for distribution. There are also constraints in routine operations to ensure the use of the most efficient and secure procedures and protocols through SOP's, QMS, and research. There is an increased awareness for the need for safety duplication and many institutions are committed to secure collections with a back-up but there were significant constraints, nor it is not a clear priority for action currently. This would seem to be vulnerability for the global system that needs to continue to be corrected.

Priority needs have been identified in terms of improvements recommended for routine operations, facilities, equipment, and procedures where there are backlogs or a significant need for upgrades. Many of these are due to the reliance of the genebanks on short term specific project funds that are not recurring and seem to be declining. The financial support for long term conservation and use is not a priority for many donors and the relatively lower priority that is given internationally and nationally for sorghum has resulted in few opportunities for acquiring funds to address these gaps. The lack of global action to address these collection specific constraints is a risk for the conservation of a high proportion of the unique diversity.

There is a need for a global initiative to address the insecurity of conservation and the constraints to distribution with four activities. A very important activity will be the development of a global fund with a competitive grants program for collection holders to apply for funds that would enable them to address the upgrades. The fund could be set up to require matching funds from the government or NGOs for specific projects and a commitment to increased annual allocation to secure long-term conservation that has significant national value.

There is a general need to upgrade operations, documentation, and efficiency of conservation with the adoption of a quality management system, a genebank information management system, and more sharing of accession level data online through platforms such as Genesys. The coordinated, collective action of most of the major collection holders would be an opportunity to share resources, experiences, and capacity globally. **Thus, there is a need to ensure that there is a global working group of conservation and use experts that would have an important role in setting priorities and targets for projects,**

ensuring global collaborating on projects if needed, monitoring the projects, and communicating the results.

While national exchange and distribution seems to be more constrained by lack of knowledge of the accessions and inadequate seed availability, international distribution is additionally constrained by policies as well as the cost and complexity of shipment with the need for phytosanitary certificates, and appropriate packaging. There may be a need to explore options to cover this cost or to charge the requestor of the germplasm. This could be supported by the global fund.

For the future sustainability of the improvements made through the investment in the two top priority actions, there is a need to facilitate the establishment of a platform that will enable the conservers of sorghum genetic resources to collaborate with and establish priorities with users that leads to enhancing the value of these global holdings. This coordinated activity will need to link the key collection holders, key users, and other stakeholders. It will allow for ex situ conservation holders to share experiences; collectively improve conservation practices; establish quality management system protocol, processes, and standards; offer each other capacity building opportunities; address the need for safety duplication; facilitate genebank information systems adoption and accession level sharing. This platform can also address the declining financial support for specific collection or localities at risk of loss due to natural disasters, reduction in the importance of the crop, loss of resources, loss of expertise, and other causes that might require an urgent action. The platform could also serve as a convener for a global collaborative project to assess duplications and identify global gaps bsed on needs in regional crop improvement programs. This platform could be operated virtually with in-person meeting when funds are available. Global collections, such as ICRISAT, USDA-ARS, NBPGR, AGG in Australia, EMBRAPA in Brazil, and some of the key national collection holders could serve as this foundational group. It would not be a network with a formal structure or leadership, but it would need to have a commitment for facilitation.

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Acronyms

Access and benefit sharing	ABS
Chinese Academy for Agricultural Sciences	CAAS
Democratic Republic of Congo	DRC
European Cooperative Programme for Plant Genetic Resources	ECPGR
Food and Agriculture Organization	FAO
Institut de recherche pour le développement	IRD
International Centre for Research in the Semi-Arid Tropics	ICRISAT
International Institute for Tropical Agriculture	IITA
International Plant Genetic Resources Institute	IPGRI
International Treaty for Plant Genetic Resources for Food and Agriculture	ITPGRFA
M.S. Swaminathan Research Foundation	MSSRF
material transfer agreement	MTA
National Agricultural Research Organization	NARO
Non-Governmental Organization	NGO
quality management system	QMS
SPGRC Documentation and Information System	SDIS
SADC Plant Genetic Resources Center	SPGRC
Standard material transfer agreement	SMTA

standard operating procedures	SOP
United States Department of Agriculture- Agricultural Research Service	USDA-ARS
Foreign Agricultural Service/United States Department of Agriculture	FAS/USDA
N. I. Vavilov Institute of Plant Genetic Resources	VIR

Literature Cited

Adugna, A., 2014. Analysis of in situ diversity and population structure in Ethiopian cultivated Sorghum bicolor (L.) landraces using phenotypic traits and SSR markers. Springerplus 3, 212.

Adugna A, Sweeney PM, Bekele E. 2013 Estimation of in situ mating systems in wild sorghum (Sorghum bicolor (L.) Moench) in Ethiopia using SSR-based progeny array data: implications for the spread of crop genes into the wild. J Genet. 92(1):3-10. doi: 10.1007/s12041-013-0214-6. PMID: 23640403.

Alercia A. 2011. Key Characterization and Evaluation Descriptors: Methodologies for the Assessment of 22 Crops. Bioversity International, Rome, Italy.

Amelework, B., Shimelis, H., Tongoona, P., Laing, M., & Mengistu, F. 2015. Genetic variation in lowland sorghum (Sorghum bicolor (L.) Moench) landraces assessed by simple sequence repeats. Plant Genetic Resources, 13(2), 131-141. doi:10.1017/S1479262114000744

Ananda GKS, Myrans H, Norton SL, Gleadow R, Furtado A and Henry RJ 2020 Wild Sorghum as a Promising Resource for Crop Improvement. Front. Plant Sci. 11:1108. doi: 10.3389/fpls.2020.01108

Barnaud, A., Deu, M., Garine, E., Chantereau, J., Bolteu, J., Koïda, E. O., et al. (2009). A weed–crop complex in sorghum: The dynamics of genetic diversity in a traditional farming system. Am. J. Bot. 96, 1869–1879. doi: 10.3732/ ajb.0800284

Barro-Kondombo, Clarisse, Fabrice Sagnard, Jacques Chantereau, Monique Deu, Kirsten vom Brocke, Patrick Durand, Eric Goze´, and Jean Didier Zongo 2008 Genetic structure among sorghum landraces as revealed by morphological variation and microsatellite markers in three agroclimatic regions of Burkina Faso Theor Appl Genet DOI 10.1007/s00122-010-1272-2

Batey I (2017) The diversity of uses for cereal grains. In: Wrigley C, Batey I, Miskelly D (eds) Cereal grains. Elsevier, Amsterdam, Netherlands, pp 41–53

Bhagavatula S, Parthasarathy Rao P, Basavaraj G and Nagaraj N. 2013. Sorghum and Millet Economies in Asia – Facts, Trends and Outlook. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 80 pp. ISBN: 978-92-9066-557-1.

Billot C, Ramu P, Bouchet S, Chantereau J, Deu M, Rivallan R, Li Y, Lu P, Gardes L, Noyer J, Wang T, Folkertsma RT, Arnaud E, Upadhyaya HD, Glaszmann C, and Hash CT (2013) Massive sorghum collection genotyped with SSR Markers to enhance use of global genetic resources. PLoS ONE 8(4):e59714

Boyles, Richard E., Zachary W. Brenton and Stephen Kresovich 2019 Genetic and genomic resources of sorghum to connect genotype with phenotype in contrasting environments. The Plant Journal 97, 19–39

Brink M and van Hintum T (2020) Genebank Operation in the Arena of Access and Benefit-Sharing Policies. Front. Plant Sci. 10:1712. doi: 10.3389/fpls.2019.01712

Bucheyekei, T.L., Gwanama, C., Mgonja, M., Chisi, M., Folkertsma, R. and Mutegi, R. (2009) Genetic Variability Characterisation of Tanzania Sorghum Landraces Based on Simple Sequence Repeats (SSRs) Molecular and Morpho logical Markers. Journal of African Crop Science, 17, 71-86.

Burow, G., Franks, C. D., Xin, Z. and Burke, J. J., 2012. Genetic diversity in a collection of Chinese sorghum landraces assessed by microsatellites. Am. J. Plant Sci. 03, 1722–9.

Casa AM, Pressoir G, Brown PJ, Mitchell SE, Rooney WL, Tuinstra MR, Franks CD, and Kresovich S. 2008 Community resources and strategies for association mapping in sorghum. Crop Sci.;48(1):30–40

Cuevas HE, and LK. Prom (2020) Evaluation of genetic diversity, agronomic traits, and anthracnose resistance in the NPGS Sudan sorghum core collection. BMC Genom 21:88–102

Cuevas HE, Rosa-Valentin G, Hayes CM, Rooney WL, Hoffmann L (2017) Genomic characterization of a core set of the USDANPGS Ethiopian sorghum germplasm collection: implications for germplasm conservation, evaluation, and utilization in crop improvement. BMC Genom 18:108–124Dahlberg, J. A. (2000), "Classification and Characterization of Sorghum", in Smith, C. W. and R. A. Frederiksen (eds.), Sorghum: Origin, History, Technology, and Production, John Wiley & Sons, New York, pp. 99-130.

Dahlberg, J. and D.T. Rosenow. 2018. Classifying the genetic diversity of sorghum: a revised classification of sorghum. IN: Rooney, W. (ed.), Achieving sustainable cultivation of sorghum Volume 1: Genetics, breeding and production techniques, Burleigh Dodds Science Publishing, Cambridge, UK

Dahlberg,Jeff, Melanie Harrison, Hari D. Upadhyaya, M. Elangovan, S. Pandey, and Harvinder Singh Talwar 2018. Global Status of Sorghum Genetic Resources Conservation IN V. A Tonapi et al. (eds.), Sorghum in the 21st Century: Food – Fodder – Feed – Fuel for a Rapidly Changing World, https://doi.org/10.1007/978-981-15-8249-3_3 pg 48-64

Danquah, Andrews, Isaac K. A. Galyuon, Emmanuel P. Otwe and Daniel K. A. Asante 2019 Genetic diversity in some Ghanaian and Malian sorghum [Sorghum bicolor (L) Moench] accessions using SSR markers African J of Biotechnology 18:591-602 DOI: 10.5897/AJB2019.16767

Dj`, Yao, Myriam Heuertz, Mohamed Ater, Claude Lef`ebvre, and Xavier Vekemans 2004 In situ estimation of outcrossing rate in sorghum landraces using microsatellite markers Euphytica 138: 205–212

de Wet, J.M.J. 1978. Systematics and evolution of Sorghum sect. Sorghum (Gramineae). Amer. J. Bot. 65: 477–484.

de Wet, J. M. J. and J. R. Harlan (1971), "The Origin and Domestication of Sorghum bicolor", Economic Botany, Vol. 25, pp. 128-135.

Deu, M. et al. (2006), "A Global View of Genetic Diversity in Cultivated Sorghums Using a Core Collection", Genome, Vol. 49, pp. 168-180.

Deu, M, Sagnard, F, Chantereau, J, Calatayud, C, Vigouroux, Y, Pham, JL, Mariac, C, Kapran, I, Mamadoo, A, Gerard, B, Ndjeunga, J and Bezancon, G (2010) Spatio-temporal dynamics of genetic diversity in Sorghum bicolor in Niger. Theoretical and Applied Genetics 120: 1301–1313.

Doggett H (1988) Sorghum (Longman Scientific and Technical, New York).

Dossou-Aminon, Innocent, Laura Yêyinou Loko, Arlette Adjatin, Eben-Ezer B. K. Ewédjè, Alexandre Dansi, Sujay Rakshit, Ndiaga Cissé, Jagannath Vishnu Patil, Clément Agbangla, Ambaliou Sanni, Akpovi Akoègninou, and Koffi Akpagana. 2015. Genetic Divergence in Northern Benin Sorghum (Sorghum bicolor L. Moench) Landraces as Revealed by Agromorphological Traits and Selection of Candidate Genotypes. The Scientific World Journal. Volume 2015:916476 http://dx.doi.org/10.1155/2015/916476

Duncan RR, Bramel-Cox PJ and Miller FR. 1991. Contributions of introduced sorghum germplasm to hybrid development in the US. Pages 69−102 in Use of Plant Introductions in

Cultivar Development, Part 1, CSSA Special Publication 117, (Shands HL and Wiesner LE, eds.). Madison, WI: Crop Science Society of America.

Engels, J.M.M.; Ebert, A.W. 2021a. A Critical Review of the Current Global Ex Situ Conservation System for Plant Agrobiodiversity. I. History of the Development of the Global System in the Context of the Political/Legal Framework and Its Major Conservation Components. Plants 2021, 10, 1557. https://doi.org/10.3390/plants10081557

Engels, J.M.M.; Ebert, A.W. 2021b. A Critical Review of the Current Global Ex Situ Conservation Systemfor Plant Agrobiodiversity. II. Strengths and Weaknesses of the Current Systemand Recommendations for Its Improvement. Plants 2021, 10, 1904. https://doi.org/10.3390/plants10091904

FAO. 2014. Genebank Standards for Plant Genetic Resources for Food and Agriculture. Rev. ed. Rome.

FAO (UN Food and Agriculture Organization). 2021. FAOSTAT Available at www.fao.org/faostat/en/#data/QC (accessed October 5, 2021).

FAO-WIEWS. 2020. WIEWS - World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture. Ex Situ Search. http://www.fao.org/wiews/data/ex-situ-sdg-251/search/en/?no_cache=1 Assessed June 2020.

Faye JM, Maina F, Hu ZB, Fonceka D, Cisse N, Morris GP (2019) Genomic signatures of adaptation to Sahelian and Soudanian climates in sorghum landraces of Senegal. Ecol Evol 9:6038–6051

Fernandez, M. G. S., Okeno, J. A., Mutegi, E., Fessehaie, A., and Chalfant, S. (2014). Assessment of genetic diversity among sorghum landraces and their wild/weedy relatives in western Kenya using simple sequence repeat (SSR) markers. Conserv. Genet. 15, 1269–1280. doi: 10.1007/s10592-014-0616-x

Fernie, A. R., and Yan, J. (2019). De novo domestication: An alternative route toward new crops for the future. Mol. Plant 12 (5), 615–631. doi: 10.1016/ j.molp.2019.03.016

Figueiredo, L. F. et al. (2008), “Phylogeographic Evidence of Crop Neodiversity in Sorghum”, Genetics, Vol. 179, pp. 997-1008.

Foreign Agricultural Service/United States Department of Agriculture (FAS/USDA). 2021 Grain: World Markets and Trade. Sept 2021. Pg 38-40

Galluzzi , Gea, Ase a Seyoum, Michael Halewood, Isabel López Noriega, and Eric W. Welch. 2019 The Role of Genetic Resources in Breeding for Climate Change: The Case of Public Breeding Programmes in Eighteen Developing Countries Plants 2020, 9, 1129; doi:10.3390/plants9091129

Genesys 2020 In https://www.genesys-pgr.org/ Accessed on July 4, 2020

Ghebru, B., Schmidt, R.J. and Bennetzen, J.L. (2002) Genetic Diversity of Eritrea Sorghum Landraces Assessed withSimple Sequence Repeats (SSR) Markers. Theoretical and Applied Genetics, 105, 229-236. http://dx.doi.org/10.1007/s00122-002-0929-x

Girma, Gezehegn, Habte Nida, Alemu Tirfessa, Dagnachew Lule, Tamirat Bejiga, Amare Seyoum, Moges Mekonen, Amare Nega, Kebede Dessalegn, Chemeda Birhanu, Alemnesh Bekele, Adane Gebreyohannes, Getachew Ayana, Tesfaye Tesso, Gebisa Ejeta, and Tesfaye Mengiste. 2020. A comprehensive phenotypic and genomic characterization of Ethiopian sorghum germplasm defines core collection and reveals rich genetic potential in adaptive traits. Plant Genome. 2020;13:e20055. https://doi.org/10.1002/tpg2.20055

Girma G, Nida H, Seyoum A, Mekonen M, Nega A, Lule D, Dessalegn K, Bekele A, Gebreyohannes A, Adeyanju A, Tirfessa A, Ayana G, Taddese T, Mekbib F, Belete K, Tesso

T, Ejeta G, Mengiste T (2019) A large-scale genome-wide association analyses of Ethiopian sorghum landrace collection reveal loci associated with important traits. Front Plant Sci 10:691–705

Gollin, D. (2020). Conserving genetic resources for agriculture: economic implications of emerging science. Food Security 12(5), 919–927. https :/ /do i .org /10 .1 007 /s 12571-020 -01035 -w

Gollin, D., Smale, M., Skovmand, B. (2000). Searching an ex situ collection of wheat genetic resources. American Journal of Agricultural Economics, 82(4), 812–827.

Halewood, Michael, Nelissa Jamora, Isabel Lopez Noriega, Noelle L. Anglin, Peter Wenzl, Thomas Payne, Marie-Noelle Ndjiondjop, Luigi Guarino, P. Lava Kumar, Mariana Yazbek, Alice Muchugi, Vania Azevedo, Marimagne Tchamba, Chris S. Jones, Ramaiah Venuprasad, Nicolas Roux, Edwin Rojas and Charlotte Lusty 2020 Germplasm Acquisition and Distribution by CGIAR Genebanks Plants 2020, 9, 1296; doi:10.3390/plants9101296

Hay, F.R.; Sershen, N. New Technologies to Improve the Ex Situ Conservation of Plant Genetic Resources; Burleigh Dodds Series inAgricultural Science; Burleigh Dodds Science Publishing Limited: Cambridge, UK, 2021; pp. 1–32.

Huaiqing Hao1 · Zhigang Li1 · Chuanyuan Leng1 · Cheng Lu1,3 · Hong Luo1 · Yuanming Liu1,3 · Xiaoyuan Wu1 ·Zhiquan Liu1 · Li Shang1 · Hai-Chun Jing1,2,3 2021. Sorghum breeding in the genomic era: opportunities and challenges Theoretical and Applied Genetics https://doi.org/10.1007/s00122-021-03789-z

Hyman, Glenn, Elizabeth Barona, Chandrashekhar Biradar , Edward Guevara, John Dixon, Steve Beebe, Silvia Elena Castano, Tunrayo Alabi, Murali Krishna Gumma, Shoba Sivasankar, Ovidio Rivera, Herlin Espinosa, and Jorge Cardona. 2016. Priority regions for research on dryland cereals and legumes [version 2; referees: 2 approved] F1000Research 2016, 5:885 (doi: 10.12688/f1000research.8657.2)

IBPGR and ICRISAT. (1993). Descriptors for sorghum Sorghum bicolor (L.) Moench. International Board for Plant Genetic Resources, Rome, Italy; International Crops Research Institute for the Semi-Arid Tropics, Pantacheru, India.

Jannink, Jean-Luc 2010 Dynamics of long-term genomic selection Genetics Selection Evolution 2010, 42:35

Jordan DR, Mace ES, Cruickshank AW, Hunt CH, Henzell RG (2011) Exploring and exploiting genetic variation from unadapted sorghum germplasm in a breeding program. Crop Sci 51:1444–1457

Klein, Robert R., John E. Mullet, David R. Jordan, Frederick R. Miller, William L. Rooney, Monica A. Menz, Cleve D. Franks, and Patricia E. Klein 2008 The Effect of Tropical Sorghum Conversion and Inbred Development on Genome Diversity as Revealed by High-Resolution Genotyping Crop Sci. 48(S1) S12–S26

Kuhlman, L. C., Burson, B. L., Stelly, D.M., Klein, P. E., Klein, R. R., Price, H., et al. (2010). Early-generation germplasm introgression from Sorghum macrospermum into sorghum (S. bicolor). Genome 53 (6), 419–429. doi: 10.1139/g10-027

Labeyrie, V., Deu, M., Barnaud, A., Calatayud, C., Burion, M., Wanbugu, P., Manel, S., Glaszmann, N.-C. and Leclerc, C., 2014. Influence of ethnolinguistic diversity on the sorghum genetic patterns in subsistence farming systems in eastern Kenya. PLoS One 9(3), e92178.

Lasky JR, Upadhyaya HD, Ramu P, Deshpande S, Hash CT, Bonnette J, Juenger TE, Hyma K, Acharya C, Mitchell SE, et al. 2015 Genome-environment associations in sorghum landraces predict adaptive traits. Sci Adv.1:e1400218

Leclerc, Christian and Geo Coppens d'Eeckenbrugge 2012 Social Organization of Crop Genetic Diversity. The G × E × S Interaction Model Diversity 2012, 4, 1-32; doi:10.3390/d4010001

Li, H.; Rasheed, A.; Hickey, L.T.; He, Z. Fast-forwarding genetic gain. Trends Plant Sci. 2018, 23, 184–186, doi:10.1016/j.tplants.2018.01.007.

Mace ES, Tai SS, Gilding EK, Li YH, Prentis PJ, Bian LL, Campbell BC, Hu WS, Innes DJ, Han XL, Cruickshank A, Dai CM, Frère C, Zhang HK, Hunt CH, Wang XY, Shatte T, Wang MM, Su Z, Li J, Lin XZ, Godwin ID, Jordan DR, Wang J (2013) Wholegenome sequencing reveals untapped genetic potential in Africa's indigenous cereal crop sorghum. Nat Commun 4:2320–2328

Missihoun, Antoine Abel, Hubert Adoukonou-Sagbadja, Paulin Sedah, Rollande Alade Dagba, Corneille Ahahanzo, and Clement Abgangla. 2015. Genetic diversity of Sorghum bicol (L.) Moench landraces from Northwestern Benin as revealed by microsatellite markers. African J of Biotechnology 14:1346-1353.

Mofokeng, Alina, Hussein Shimelis, Pangirayi Tongoona and Mark Laing 2014 A genetic diversity analysis of South African sorghum genotypes using SSR markers South African Journal of Plant and Soil 2014, 31(3): 145–152
http://dx.doi.org/10.1080/02571862.2014.923051

Mujaju, Claid, and Ereck Chakauya. 2008. Morphological variation of sorghum landrace accessions on-farm in semi-arid areas of Zimbabwe. International J of Botony 4: 376-382

Mundia, Clara W., Silvia Secchi, Kofi Akamani, and Guangxing Wang. 2019. A Regional Comparison of Factors Affecting Global Sorghum Production: The Case of North America, Asia and Africa's Sahel. Sustainability 2019, 11, 2135; doi:10.3390/su11072135

Mutegi, E., Sagnard, F., Muraya, M., Kanyenji, B., Rono, B., Mwongera, C., et al. (2010). Ecogeographical distribution of wild, weedy and cultivated Sorghum bicolor (L.) Moench in Kenya: implications for conservation and crop-to-wild gene flow. Genet. Resour. Crop Evol. 57, 243–253. doi: 10.1007/s10722-009-9466-7

Mutegi, E., Sagnard, F., Semagn, K., Deu, M., Muraya, M., Kanyenji, B., et al. (2011). Genetic structure and relationships within and between cultivated and wild sorghum (Sorghum bicolor (L.) Moench) in Kenya as revealed by microsatellite markers. Theor. Appl. Genet. 122, 989–1004. doi: 10.1007/s00122-010-1504-5

Mutegi, E., Sagnard, F., Labuschagne, M., Herselman, L., Semagn, K., Deu, M., et al. (2012). Local scale patterns of gene flow and genetic diversity in a crop–wild–weedy complex of sorghum (Sorghum bicolor (L.) Moench) under traditional agricultural field conditions in Kenya. Conserv. Genet. 13, 1059–1071. doi: 10.1007/s10592-012-0353-y

Myrans, Harry, Maria V. Diaz, Colin K. Khoury, Daniel Carver, Robert J. Henry, and Roslyn Gleadow 2020 Modelled distributions and conservation priorities of wild sorghums (Sorghum Moench) Diversity and Distributions. 2020;26:1727–1740. DOI: 10.1111/ddi.13166

Naoura, Gapili, Nerbewende Sawadogo, Eyanawa A. Atchozou, Yves Emendack, Mahamat A. Hassan, Djinodji Reoungal, Doyam N. Amos, Nadjiam Djirabaye, Ramadjita Tabo and Haydee Laza. 2019 Assessment of agro-morphological variability of dry-season sorghum cultivars in Chad as novel sources of drought tolerance. Scientific Reports 9:19581 https://doi.org/10.1038/s41598-019-56192-6

Ng'uni, D, Geleta, M and Bryngelsson, T (2011) Genetic diversity in sorghum (Sorghum bicolor (L.) Moench) accessions of Zambia as revealed by simple sequence repeats (SSR). Hereditas 148: 52–68.

Nguyen, Giao N., and Sally L. Norton 2020 Genebank Phenomics: A Strategic Approach to Enhance Value and Utilization of Crop Germplasm Plants 2020, 9, 817; doi:10.3390/plants9070817

NIKIEMA, S. Zara, Jacob SANOU, Banse OUEDRAOGO, Vernon GRACEN, B. Pangirayi TONGOONA and Samuel Offei KWAME 2020 Genetic diversity of sorghum (Sorghum bicolor (L) Moench) accessions from thirteen regions of Burkina Faso Int. J. Biol. Chem. Sci. 14(5): 1547-1557

OECD. 2016. Consensus Document on the Biology of Sorghum (Sorghum bicolor L. Moench). OECD Environment, Health and Safety Publications, Series on Harmonisation of Regulatory Oversight in Biotechnology, No. 62, Organization for Economic Co-operation and Development: Paris, France.

Ohadi, S., Hodnett, G., Rooney, W., and Bagavathiannan, M. (2017). Gene Flow and its Consequences in Sorghum spp. Crit. Rev. Plant Sci. 36, 367–385. doi:10.1080/07352689.2018.1446813

Okeno, J. A., Mutegi, E., De Villiers, S., Wolt, J. D., and Misra, M. K. (2012). Morphological Variation in the Wild-Weedy Complex of Sorghum bicolor In Situ in Western Kenya: Preliminary Evidence of Crop-to-Wild Gene Flow? Int. J. Plant Sci. 173, 507–515. doi: 10.1086/665266

Orr, A., C. Schipmann-Schwarze, A. Gierend, S. Nedumaran. C. Mwema, E. Muange, E. Manyasa, and H. Ojulong. 2020. Why invest in Research & Development for sorghum and millets? The business case for East and Southern Africa. Global Food Security 26 (2020) 100458 https://doi.org/10.1016/j.gfs.2020.100458

Prasad, V.B.R.; Govindaraj, M.; Djanaguiraman, M.; Djalovic, I.; Shailani, A.; Rawat, N.; Singla-Pareek, S.L.; Pareek, A.; Prasad, P.V.V. Drought and High Temperature Stress in Sorghum: Physiological, Genetic and Molecular Insights, and Breeding Approaches. Int. J. Mol. Sci. 2021, 22, 9826. https://doi.org/10.3390/ ijms22189826

Qingshan, Lu, and Jeffery A. Dahlberg 2001 Chinese Sorghum Genetic Resources Econ botony 55: 401-425

Rabbi, I. Y., Geiger, H. H., Haussmann, B. I. G., Kiambi, D., Folkertsma, R. and Parzies, H. K., 2010. Impact of farmers’ practices and seed systems on the genetic structure of common sorghum varieties in Kenya and Sudan. Plant Genet. Resour. Charact. Util. 8, 116–26.

Reddy BVS, Kumar AA, Reddy PS, Elangovan M (2008) Sorghum germplasm: diversity and utilization. In: Bantilan MCS, Deb UK, Gowda CLL, Reddy BVS, Obilana AB, Evenson RE (eds) Sorghum genetic enhancement: research process, dissemination and impacts. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, AP, India, pp 153–169. ISBN 978-92-9066-512-0

Rosenow, D.T., and J.A. Dahlberg. 2000. Collection, conversion and utilization of sorghum. p. 305–328. In C.W. Smith and R.A. Frederiksen (ed.) Sorghum: Origin, history, technology, and production. John Wiley & Sons, New York.

Sagnard, F., Deu, M., Dembélé, D., Leblois, R., Touré, L., Diakité, M., et al. (2011). Genetic diversity, structure, gene flow and evolutionary relationships within the Sorghum bicolor wild–weedy–crop complex in a western African region. Theor. Appl. Genet. 123, 1231. doi: 10.1007/s00122-011-1662-0

Sagnard F, Deu M, Dembélé D, Leblois R, Touré L, Diakité M, Calatayud C, Vaksmann M, Bouchet S, Mallé Y, Togola S, Traoré PC. Genetic diversity, structure, gene flow and evolutionary relationships within the Sorghum bicolor wild-weedy-crop complex in a western African region. Theor Appl Genet. 2011 Nov;123(7):1231-46. doi: 10.1007/s00122-011-1662-0. Epub 2011 Aug 3. PMID: 21811819.

Sawadogo-Lingani H, Owusu-Kwarteng J, Glover R, Diawara B, Jakobsen M and Jespersen L (2021) Sustainable Production of African Traditional Beers With Focus on Dolo, a West African Sorghum-Based Alcoholic Beverage. Front. Sustain. Food Syst. 5:672410. doi: 10.3389/fsufs.2021.672410

Smith, C. W. and R. A. Frederiksen (2000), "History of Cultivar Development in the United States: From "Memoirs of A.B. Maunder - Sorghum Breeder"", in Smith, C. W. and R. A. Frederiksen (eds.), Sorghum: Origin, History, Technology, and Production, John Wiley & Sons, New York, pp. 191-223.

Smale, Melinda, Nelissa Jamora, and Luigi Guarino 2021. Valuing plant gentic resources in genbanks: Past, present and future. IN Dulloo, M. E. (ed.), Plant genetic resources: A review of current research and future needs, Burleigh Dodds Science Publishing, Cambridge, UK http://dx.doi.org/10.19103/AS.2020.0085.02

Stephens, J.C., F.R. Miller, and D.T. Rosenow. 1967. Conversion of alien sorghum to early combine types. Crop Sci. 7:396.

Tack, Jesse, and Jane Lingenfelser and S. V. Krishna Jagadish. 2017. Disaggregating sorghum yield reductions under warming scenarios exposes narrow genetic diversity in US breeding programs. Proceedings of the National Academy of Sciences. 114: 9296-9301. doi =10.1073/pnas.1706383114

Tesso, T., Kapran, I., Grenier, C., Snow, A., Sweeney, P., Pedersen, J., et al. (2008). The potential for crop-to-wild gene flow in sorghum in Ethiopia and Niger: a geographic survey. Crop Sci. 48, 1425–1431. doi: 10.2135/cropsci2007.08.0441

Tovignan TK, Luquet D, Fonceka D, Ndoye, Trouche G, Cisse N. 2015. Assessment of the variability of Senegalese landraces for phenology and sugar yield components to broaden the genetic pool of multi-purpose sorghum. Plant Genetic Resources, 14(2): 121-131. DOI: https://doi.org/10.1017/S1479262115000155

Upadhyaya H.D., Gopal Reddy V. and Sastry D.V.S.S.R. 2008. Regeneration guidelines: sorghum. In: Dulloo M.E., Thormann I., Jorge M.A. and Hanson J., editors. Crop specific regeneration guidelines [CD-ROM]. CGIAR System-wide Genetic Resource Programme, Rome, Italy. 8 pp.

Upadhyaya, H. D., Reddy, K. N., Vetriventhan, M., Krishna, G. M., Ahmed, M. I., Reddy, M. T. and Singh, S. K., 2016b. Status, genetic diversity and gaps in sorghum germplasm from South Asia conserved at ICRISAT genebank. Plant Genet. Resour. 13, 247–55.

Upadhyaya, H. D., Reddy, K. N., Vetriventhan, M., Murali, K. G., Irshad, A. M., Manyasa, E., Reddy M.T. and Singh, S. K., 2017a. Geographical distribution, diversity and gap analysis of East African sorghum collection conserved at the ICRISAT genebank. Aust. J. Crop Sci. 11(4): 424–37.

Upadhyaya, H. D., Reddy, K. N., Vetriventhan, M., Irshad, A. M., Murali, K. N., Reddy T. M. and Singh, S. K., 2017c. Sorghum germplasm from West and Central Africa maintained in the ICRISAT genebank: Status, gaps, and diversity. The Crop Journal. doi:10.1016/j.cj.2017.07.002.

Upadhyaya, Hari D., and Mani Vetriventhan 2018 Ensuring the genetic diversity of sorghum. IN Rooney, W. (ed.), Achieving sustainable cultivation of sorghum Volume 1: Genetics, breeding and production techniques, Burleigh Dodds Science Publishing, Cambridge, UK, 2018 http://dx.doi.org/10.19103/AS.2017.0015.06

Upadhyaya, Hari D., Mani Vetriventhan and Santosh Deshpande 2016 Sorghum Germplasm Resources Characterization and Trait Mapping IN S. Rakshit and Y.-H. Wang (eds.), The Sorghum Genome, Compendium of Plant Genomes, DOI 10.1007/978-3-319-47789-3_4

USDA, Agricultural Research Service, National Plant Germplasm System. 2021. Germplasm Resources Information Network (GRIN Taxonomy). National Germplasm Resources Laboratory, Beltsville, Maryland. URL: https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomydetail?id=35142. Accessed 13 October 2021.

YU, Xiaoqing, Xianran Li, Tingting Guo, Chengsong Zhu, Yuye Wu, Sharon E. Mitchell, Kraig L. Roozeboom, DonghaiWang, Ming Li Wang, Gary A. Pederson, Tesfaye T. Tesso, Patrick S. Schnable, Rex Bernardo and Jianming Yu 2016 Genomic prediction contributing to a promising global strategy to turbocharge gene banks. Nature Plants 16150 DOI: 10.1038/NPLANTS.2016.150

Zereyesus YA, Dalton TJ (2017) Rates of return to sorghum and millet research investments: A meta-analysis. PLoS ONE 12(7): e0180414. https://doi.org/10.1371/journal.pone.0180414

Wiersema, John H. and Jeff Dahlberg 2007. The nomenclature of Sorghum bicolor (L.) Moench (Gramineae) TAXON 56 (3) August 2007: 941–946

Weise, Stephan, Ulrike Lohwasser and Markus Oppermann 2020 Document or Lose It—On the Importance of Information Management for Genetic Resources Conservation in Genebanks. Plants 2020, 9, 1050; doi:10.3390/plants9081050

Annex I. Respondents to the 2021 survey

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ARE003	International Center for Biosaline Agriculture (ICBA)	Dubai, 14660, UAE	Muhammad Shahid
ARG	Instituto Nacional de Tecnología Agropecuaria (INTA)	Manfredi 5988, Argentina	Diego Ortiz
AUS165	Australian Tropical Grains Germplasm Centre Crop and Food Science Agri-Science Agriculture Victoria	110 Natimuk Road, Horsham, 3400, Australia	Dr Sally Norton
BEN	Centre of Agricultural Research of the North West / National Institute of Agricultural Research of Benin (CRA-NO/INRAB)	Natitingou, BP 545, Benin	Guirguissou MABOUDOU ALIDOU
BFA	INERA Saria	BP 10, Koudougou, Burkina Faso	Clarisse Pulchérie Barro Kondombo
BRA003	EMBRAPA Recursos Geneticos e Biotecnologia (CENARGEN)	Peb A. W5 Norte (final), Brasilia, 70770-901, Brazil	Juliano Gomes Pádua
BWA015	Botswana National Plant Genetic Resources Centre	Department of Agricultural Research, Private Bag 0033, Gaborone, Botswana	Dr Tiny Mpho Motlhaodi
ERI003	Ministry of Agriculture, National Agricultural Research Institute, Halhale	Asmara, 4627, Eritrea	Amanuel Mahdere Zerezghi
ESP004	Spain Instituto Nacional de Investigacion y Tecnologia Agraria y Alimentaria. Centro National de Recursos Fitogeneticos, INIA.	Autovía A-2, km. 36. Apdo 1045, Alcala de Henares 28805, Spain	Isaura Martin
ETH085	Ethiopian Biodiversity Institute	Addis Ababa, PO Box 30726, Ethiopia	Wubishet Teshome and Eyerusalem Arusi
GBR004	Royal Botanic Gardens Kew/ Millennium Seed Bank, Wakehurst Place	Ardingly, West Sussex, United Kingdom	Janet Terry
GHA	CSIR- Savanna Agricultural Research Institute, Sorghum Improvement Section	P. O. Box TL 52, Tamale-Ghana.	Kenneth Opare-Obuobi
GHA091	CSIR-Plant Genetic Resources Research Institute	P.O.Box 7 Bunso, Ghana	Dr Lawrence Misa Aboagye and Dr Rashied Tetteh
HND005	Escuela Agrícola Panamericana El Zamorano	Tegucigalpa Honduras	Dr. Juan Carlos Rosas
IND001	ICAR-National Bureau of Plant Genetic Resources	New Dehli, 110012, India	Dr Sushil Pandey
IND002	ICRISAT Niamey Regional Genebank	Niamey, BP 12404, Niger	Dr. Hamidou Falalou
IND002	ICRISAT	502324 Hyderabad, India	Dr Vania Azevedo, Mani Vetriventhan, Ovais Peerzada, Venkata Narayana
IND0182	ICAR-Indian Institute of Millets Research (IIMR)	Hyderabad 500030, Telangana, India	Dr. M. Elangoven
KEN212	Genetic Resources Research Institute	P.O. Box 781 00902, Kikuyu, Kenya	Dr. Desterio Nyamongo and Joseph Ndungu Kimani

LKA036	Sri Lanka Plant Genetic Resources Centre, Gannoruwa	Peradeniya 20400, Sri Lanka	Mr. S. Wanigadeva and Dr. D.G.C. Jeewani
LSO015	Lesotho National Plant Genetic Resources Center	Maseru, 100, Lesotho	Matsikoane Sefotho
MAR088	INRA Genebank - Centre Régional de la Recherche Agronomique de Settat	Route tertiaire 1406, A 5 Km de Settat Maroc, 26000	Dr, Hassan Ouabbou
MLI070	Unite des Ressources Genetique (UGR),	Institute d'Economie Rurale, Bamako, BP 258, Mali	Amadou Sidibe
NAM006	Namibia National Plant Genetic Resources Center,	Hugel Street, Windhoek, 9000, Namibia	Heleni Heita and Remmie Hilukwa
NER001	Niger Institut national de la recherche agronomique du Niger (INRAN)	Corniche Yantala BP 429 Niamey Niger	Mahaman Mourtala Issa Zakari and Baina Danjimo
NGA010	National Centre for Genetic Resources and Biotechnology	Ibadan, PMB 5382, Nigeria	Dr. Sunday E. Aladele
NPL069	Nepal National Agriculture Genetic Resources Centre (NAGRC), Khumaltar	Katmandu, Nepal	Dr. Bal Krishna Joshi
SDN002	Sudan Agricultural Plant Genetic Resources Conservation and Research Centre, Agricultural Research Corporation	Wad Medani, 21111, Sudan	El Tahir Ibrahim Mohamed
SEN094	Institut Sénégalais de Recherches Agricoles (ISRA)	Bel Air, routes des hydrocarbures, Dakar, BP 3120, Senegal	Cyril Diatta
TCD	Institut *Tchadien* de Recherche Agricole pour le Développement (ITRAD)	BP : 5400 N'Djamena, Tchad	Dr Gapili Naoura
TGO	Togo Institut Togolais de Recherche Agronomique (ITRA)	Siège Cacaveli Lome Togo 1163	Akata Atchozou Eyanawa and Dr Kombate Koffi
UGA132	Plant Genetic Resources Center	Entebbe, Uganda	Dr. J.W. Mulumba and Eva Zaake
USA016	PGRCU Southern Regional Plant Introduction Station USDA-ARS-SAA	1109 Experiment Street, Griffin, 30223, Georgia, USA	Melanie Harrison
ZAF062	South Africa National Plant Genetic Resources Centre	Directorate: Gentic Resources, Private Bag X973, Pretoria, 0001, South Africa	Ms. Mpolokeng Mokoena and Thabo Tjikana
ZMB030	SADC Plant Genetic Resources Centre (SPGRC)	Lusaka, Farm no. 6300, Zambia	Sthembiso A. Mbhele
ZMB048	Zambia National Plant Genetic Resources Centre, Zambia Agriculture Research Institute	Lusaka, Zambia	Graybill Munkombwe
ZWE049	Zimbabwe National Plant Genetic Resources Centre	Harare Research Center Fifth Street Extension Opposite Royal Harare Golf Club, Harare, Zimbabwe	Onismus Chipfunde

Annex II. Number of accessions reported in the 2007 Strategy Report and in 2021 in the survey or in the consolidated global database.

Country	Institute	No. of accession in 2007 Strategy Report	No of accession from survey in 2021	No of accessions in consolidated global database
Institutions that responded to the 2021 survey				
USA	USDA-ARS-PGRCU	43104	47412	
India	ICRISAT	36774	42352	
India	ICRISAT Niamey Regional Genebank		3045	
India	NBPGR	18853	25507	
India	ICAR-IIMR	2767	2183	
Ethiopia	EBI	9772	11063	
Brazil	EMBRAPA CENARGEN	8017	4726	
Zimbabwe	NPGRC	7009	2032	
Australia	AGG	5403	7107	
Sudan	PGRU-ARC	4191	7212	
Mali	IER	2975	2658	
Kenya	KALRO GRRI	1320	6287	
Zambia	NPGRC	1005	960	
South Africa	NPGRC	428	559	
Nigeria	NCGRB	159	2276	
Argentina	INTA	3251	2976	
Uganda	Serere Ag. & Animal Prod Res. Inst	2635	950	
Burkina Faso	INERA-Saria		2800	
Ghana	CSIR-Plant Genetic Resources Research Institute	67	85	
Eritrea	National Agricultural Research Institute, Halhale		722	
Honduras	Escuela Agricola Panamericana El Zamorana	2000	4	
Morocco	INRA Genebank - Centre Régional de la Recherche Agronomique de Settat	1	237	
Zambia	SADC Plant Genetic Resources Centre (SPGRC)		4658	
Niger	Institut national de la recherche agronomique du Niger (INRAN)		3445	
Senegal	Institut Sénégalais de Recherches Agricoles (ISRA)		1221	
Botswana	National Plant Genetic Resources Centre	166	506	
Ghana	CSIR-SARI Ghana		471	
Lesotho	National Plant Genetic Resources Center		435	
UAE	ICBA	319	318	
UK	Royal Botanic Gardens Kew/ Millennium Seed Bank, Wakehurst Place	9	244	
Sri Lanka	Plant Genetic Resources Centre, Gannoruwa	52	217	
Togo	Institut Togolais de Recherche Agronomique (ITRA)		212	

Country	Institute	No. of accession in 2007 Strategy Report	No of accession from survey in 2021	No of accessions in consolidated global database
Namibia	Namibia National Plant Genetic Resources Center,		192	
Chad	Institut *Tchadien* de Recherche Agricole pour le Développement (ITRAD)		139	
Benin	Centre of Agricultural Research of the North West / National Institute of Agricultural Research of Benin (CRA-NO/INRAB)		95	
Spain	Spain Instituto Nacional de Investigacion y Tecnologia Agraria y Alimentaria. Centro National de Recursos Fitogeneticos, INIA.	42	79	
Nepal	Nepal National Agriculture Genetic Resources Centre (NAGRC), Khumaltar	20	60	
Institutions that only responded to 2007 survey				
Global	ILRI	52		61
France	CIRAD	2690		
China	CAAS	18250		
Russia	VIR	7335		
Malawi	NPGRC	401		433
Serbia	Inst. Field and Vegetable crops	152		
Institutions where additional information was needed in 2007 and no response for 2021				
Mexico	INIFAP	3990		68
Japan	NIAR	2583		5053
Philippines	IPB/UPLB	2285		6
Thailand	Dept. of Ag Univ. of Kasetsart	1500		10
Colombia	CORPOICA	1290		1104
Rwanda	ISAR	1144		
Hungary	Institute for Agrobotany	1013		873
Guatemala	ICTA	823		
Bulgaria	Institute for PGR "K.Malkov"	569		1046
Pakistan	Inst. of Ag. Biotech. and GR	492		933
El Salvadore	Centa	406		25
Nicaragua	REGEN Universida Nacional Agraria	30		21
Somalia	Central Agricultural Research Station	94		
Yemen	American Sorghum Project	4000		

Annex III. The plants that feed the world: baseline data and indicators for PGRFA, with specific reference to sorghum

Khoury et al. (2021) compiled a comprehensive dataset as part of a project funded by the International Treaty on Plant Genetic Resources for Food and Agriculture (http://www.fao.org/plant-treaty/) and the Crop Trust, led by the International Center for Tropical Agriculture (CIAT, https://ciat.cgiar.org/). The aim was to introduce five normalized reproducible indicators that provide an evidence base to prioritize actions with respect to conservation and use of crop genetic resources for food and agriculture. The indicators enclose metrics associated with the USE of a crop (Global importance), the INTERDEPENDENCE between countries with respect to genetic resources, the DEMAND of researchers for genetic resources, the SUPPLY of germplasm by gene banks and the SECURITY of germplasm conservation. The indicator results are visualized publicly available on an interactive online website (https://public.tableau.com/profile/colin.khoury#!/vizhome/ITPGRFA-Indicator/ITPGRFA-Indicator?publish=yes). To generate the five indicators, Khoury et al. 2021 collected a comprehensive dataset from multiple sources. In the following, we don't present the indicators created by Khoury et al. (2021), but discuss the underlying raw data to shed light on the different aspects represented by the indicators.

To put numbers into context, we compare sorghum with maize (Table 1). Both crops are comparable with respect to type of growth, propagation and use (both are at least partly outcrossing poaceas used are cereals). *Sorghum* and *Sorghum bicolor* are the genus and species name of sorghum, respectively, *Zea* and *Zea mays* the genus and species name of maize.

The metrics for "Global production", "Food supply" and "Quantity exported globally" from the indicator domain "Crop use" are annual average values drawn from FAOSTAT data (FAOSTAT, 2019) between the years 2010-2014. The percentage of countries producing and consuming (being supplied with) the crop is calculated as the number of countries, where the respective crop is within the top 95 % of most important crops divided by the number of countries which report respective numbers (can be different between metrics and crops). The global production of sorghum is at about 59 million tons annually, which is 6 % of the global maize production (about 918 M t). The quantity of food supply by sorghum, i.e. the average global consumption is with about 10 g/cap/day at 20 % of global maize supply as food source (49 g/cap/day). Sorghum food supply is thus relatively high, compared to its production. Considering low global production of sorghum compared to maize, percentage of countries producing sorghum relatively high, in 50 % of reporting countries, sorghum ranges within the 95 % top crops. In comparison, maize is produced in 81 % of the worlds' countries. Maize is consumed in 99 % of all countries in the world, whereas sorghum consumption (food supply) is relatively restricted with only 31 % of countries. Both, maize and sorghum are internationally traded cereal crops, about 11 (Sorghum with 6 M t) and 13 % (maize with 121 M t) of their total production is being exported.

The crop use metrics with respect to research were assessed by manual search on google scholar, searching for the respective genus or species in the titles of publications, including patents and citations, between the years 2009 and 2019 (Khoury et al., 2021). Google scholar search hits represent importance with respect to scientific interest in a crop. The *Sorghum* genus is found in 15,800 publication titles, which is almost as much as publication titles including the maize genus *Zea*. However, we must take into account that genus and common name of sorghum are both "sorghum" and thus the number of publication titles including "sorghum" represent boths, genus and common name. In contrast, common names of maize are "corn" and "maize", whereas the scientific genus name is "*Zea*". Thus, numbers for the two crops are not comparable. Publications with titles including the species names *S. bicolor* and *Z. mays* are more relatable. *Sorghum bicolor* appears in 4,550 publication titles, where *Zea mays* is included in 16,300 publication titles. Sorghum research receives thus about 28 % of attention as maize research. If related to the comparison of production between both crops presented previously, sorghum research is relatively overrepresented when compared to maize research.

Khoury et al. (2021) defined interdependence as a measure for the degree of dependence of the global cultivation and use of a certain crop from germplasm present at the primary centers of diversity of the respective crop. Primary centers of diversity are not represented by countries, but by 23 agroecological zones (Khoury et al. 2016), as crop diversity does not follow national boarders but rather climatic and agroecological boundaries. Interdependence is high in crops which originate from a small area and are cultivated and used globally. For production, interdependence is calculated by dividing a crops' production outside of the primary center of diversity by the global production. If all production would be outside the primary center of diversity, interdependence would be 100 %. For food supply, interdependence is calculated by dividing the food supply by the world average. Food supply outside can be higher than inside of primary regions of diversity and thus also higher than the global mean. Therefore, interdependence with respect to food supply can be above 100 %. Primary centers of diversity of sorghum are located in Central, South, West and East Africa. As African countries like Nigeria, Ethiopia and Soudan are strong sorghum producers, interdependence of global production is with 62 % relatively low compared to maize. The interdependence value for maize is 97 %, where primary centers of diversity are in Central America and Andean South America and main producers are the United States of America and China. Interdependence of food supply of sorghum per capita is, with 41 %, much lower than interdependence with respect to production (62 %, stated above). This implies that consumption of sorghum as food source is taking place more locally within Africa, where a greater share of sorghum production outside of Africa is putatively used for non-food purposes.

Demand for germplasm is defined by two metrics (Khoury et al., 2021). First, by the number of distributions of accessions by gene banks, as an annual average between 2014 and 2017 drawn from the Plant Treaty Information System. Second, by the number of varieties released during the five years between 2014 and 2018, obtained from the International Union for the Protection of New Varieties of Plants (UPOV, https://www.upov.int). There is a relatively strong use of sorghum germplasm reflected by the 23,465 sorghum accessions per year distributed by gene banks, which is about half of yearly distributions of maize accessions (49,148). However, this is in contrast to a relatively low development of sorghum cultivars. Only 4,683 varieties of sorghums where released during a five-year period, which represents only 4 % of maize varieties released in the same time period (126,232 varieties).

Khoury et al. (2021) illustrated the supply of germplasm with the number of accessions available in ex situ collections around the world, with respect to the crop genus and the most important species of the respective crop. Furthermore, Khoury et al. (2021) assessed the number of accessions (again with respect to genus and species) which were available under the multilateral system (MLS) of the Plant Treaty (http://www.fao.org/plant-treaty/areas-of-work/the-multilateral-system). This was done first, directly, as notation (in MLS / not in MLS) in the public online databases Genesys (https://www.genesys-pgr.org), FAO WIEWS (http://www.fao.org/wiews) and GBIF (https://www.gbif.org). Secondly, availability of accessions was assessed via the status of the country where the institution was located which held the respective germplasm collection. If the country was contracting partner of the Plant Treaty, the respective accession was regarded as available via the MLS. According to databases, global ex situ collections count a total of 169,377 accession of the genus *Sorghum* including 163,242 accessions of the species *S. bicolor*. These numbers are relatively high given that global maize collections account for 213,337 *Zea* and 208,062 *Z. mays* accessions. Both, sorghum and maize are listed in Annex I of the Plant Treaty. Practically none of the sorghum accessions (< 1 %) is available under the MLS, stated directly in respective databases, in contrast 20 % of maize accessions are available under the MLS, as stated directly in respective databases. However, if counting accessions available indirectly by matching institute countries with party status, 95 % of sorghum accessions can be made available, in contrast to only 69 % of maize accessions.

Security of germplasm conservation is represented here with two metrics, the safety duplication status at the Svalbard Global Seed Vault (SGSV) and the equality of global distribution with respect to several crop use metrics. The numbers of accessions safety duplicated with respect to genus and species were drawn from the website of the SGSV (https://seedvault.nordgen.org) and divided by the total number of accessions stored in global ex situ collections (see paragraph above), resulting in the percentage of safety duplicated germplasm. To represent the equality of distribution across different agroecological regions of the world (Khoury et al., 2016), Khoury et al. (2021) used the reciprocal 1-Gini index with respect to the different crop use metrics. The Gini index is the most commonly used inequality index (Gini index, 2008), foremostly known for the quantification of global income inequality. The 1-Gini index, presented here, ranges from 0 to 1, where 0 reflects very unequal distribution across world regions, 1 would represent a completely equal global distribution of the respective metric across the worlds' regions. It reflects the security of crop cultivation and use, where e.g. small indices of production and thus geographical restriction go hand in hand with a higher vulnerability of supply, e.g. in cases of natural disasters. A relatively high number of sorghum accessions are safety duplicated at SGSV (about 23 %), compared to 15 % of all ex situ maize accessions. Equality of the distribution across the worlds' regions with respect to global production of sorghum is, with 0.05, higher than equality of distribution of maize (0.03). This is in contrast to the higher percentage of countries in the world producing a significant amount of maize compared to sorghum. We suppose that production quantity of sorghum must thus be, however, more equally distributed across regions, meaning that maize production is, in contrast, more concentrated. For equality of the distribution of food supply, there is a contrasting image. Food supply of maize is more equally distributed throughout the world with 0.15, compared to a value of 0.05 for sorghum.

Literature:

FAOSTAT (2019) Statistics for 2010-2014. www.fao.org. Accessed 2019.

Gini Index. In: The Concise Encyclopedia of Statistics (2008) Springer, New York, NY. https://doi.org/10.1007/978-0-387-32833-1_169

Khoury CK, Sotelo S, Amariles D, Guarino L, and Toledo A (2021) A global indicator of the importance of cultivated plants, and interdependence with regard to their genetic resources worldwide. Forthcoming

Khoury, C., Sotelo, S. Amariles, D. (2019) The plants that feed the world: baseline information to underpin strategies for their conservation and use. International Treaty on Plant Genetic Resources for Food and Agriculture (Rome) Project 2018 – 2019

Khoury, C. K., Achicanoy, H. A., Bjorkman, A. D., Navarro-Racines, C., Guarino, L., Flores-Palacios, X., Engels, J. M.M., Wiersema, J. H., Dempewolf, H., Sotelo S., Ramírez-Villegas, J, Castañeda-Álvarez, N. P., Fowler, C., Jarvis, A., Rieseberg, L. H., Struik, P. C. (2016). Origins of food crops connect countries worldwide. *Proceedings of the royal society B: biological sciences*, *283*(1832), 20160792.

Khoury, C. K., Achicanoy, H. A., Bjorkman, A. D., Navarro Racines, C., Guarino, L., Flores Palacios, X., Engels, J. M.M., Wiersema, J. H., Dempewolf, H., Ramírez-Villegas, J., Castañeda-Álvarez, N. P., Fowler, C., Jarvis, A., Rieseberg, L. H., Struik, P. C. (2015). Estimation of countries' interdependence in plant genetic resources provisioning national food supplies and production systems. The International Treaty, Research Study 8

Table 1. Selected metrics collected by Khoury et al. 2021 for sorghum and maize, subdivided by indicator domain

Metric	Sorghum	Maize	Sorghum / Maize
Crop use			
Global production [tons]	58,927,804	917,517,036	6%
Food supply (Amount consumed) [g/capita/day]	10	49	20%
Percentage of countries producing crop *	50%	81%	62%
Percentage of countries consuming (being supplied with) crop *	31%	99%	32%
Quantity exported globally [t]	6,378,373	120,837,238	5%
Number of publications between 2009-2019, including patents and citations, searching title of publication (Google scholar search hits) for genus **	15,800	16,400	96%
Number of publications between 2009-2019, including patents and citations, searching title of publication (Google scholar search hits) for species ***	4,550	16,300	28%
Interdependence			
Interdependence of global production from germplasm from primary centers of diversity [0-1] ****	62%	97%	64%
Interdependence of global food supply from germplasm from primary centers of diversity [0-1] ****	41%	89%	46%
Demand			
Accessions distributed from gene banks (Annual average 2014-2017)	23,465	49,148	48%
Variety releases in 5 years (2014-2018)	4,683	126,232	4%
Supply			
Number of accessions in ex situ collections of genus **	169,377	213,337	79%
Number of accessions in ex situ collections of species ***	163,242	208,062	78%
Accessions of the genus ** available through Multilateral System (MLS) directly noted in databases [%]	0%	20%	
Accessions of the species *** available through Multilateral System (MLS) directly noted in databases [%]	0%	20%	
Accessions of the genus ** available through Multilateral System (MLS) indirectly by matching institute countries with party status [%]	95%	69%	
Accessions of the species *** available through Multilateral System (MLS) indirectly by matching institute countries with party status [%]	95%	69%	
Security			
Accessions of genus ** safety duplicated in Svalbard Global Seed Vault [%]	23%	15%	
Accessions of species *** safety duplicated in Svalbard Global Seed Vault [%]	24%	15%	
1-GINI index for equality of production across the world [0-1] *****	0.05	0.03	131%

1-GINI index for equality of food supply across the world [0-1] *****	0.05	0.15	31%

* Counting countries which list the crop as within top 95 % (FAOSTAT); Calculated as: Number of countries counting crop (top 95%) / Total number of countries (production 216, food supply 175)

** Sorghum: Sorghum; Maize: Zea

*** Sorghum: Sorghum bicolor; Maize: Zea mays

**** Global metric / Metric at primary center of diversity

***** Relative equality of crop use across world regions (same regions as used in interdependence domain), high equality give high indicator value

Annex IV. Expert Consultation for Securing the Long-term Conservation and Use of Sorghum Genetic Resources Globally

23 September 2021 at 9:00-13:00 Eastern Time Zone (U.S.)

List of Participants

Participant	Affiliation
Paula Bramel	Crop Trust
Stephen Kresovich	FtF Innovation Lab for Crop Improvement USA
Jura Magalhaes	EMBRAPA Brazil
Geoff Morris	Colorado State University USA
Sarah Hearne	CIMMYT Mexico
Mitch Tunstra	Purdue University USA
Diego Ortiz	EEA Manfredi Argentina
Clarisse Pulcherie	INERA/Saria Burkina Faso
Jean-Francois Rami	CIRAD France
Gilles Trouche	CIRAD France
Dr Kuldeep Singh	ICRISAT India
Harish Gandhi	ICRISAT India
Santosh Deshpande	ICRISAT India
Mani Vetriventhan	ICRISAT India
Cyril Diatta	ISRA Senegal
M Elangovan	ICAR-IIMR India
El Tahir Ibrahim Mohamed (Ph. D.)	AGPRI Sudan
Dr. Desterio Nyamongo	GERRI-KALRO Kenya
Gebisa Ejeta	Purdue University USA
Sally Norton	AGG Australia
Vania Azevedo	ICRISAT
Naoura Gapili	ITRAD Chad

Agenda

Background: The Crop Trust is updating the global Sorghum conservation strategy, which was done in 2007. In addition to the classical approach of surveying curators about their perspectives on collection quality, gaps, challenges, etc., we desire to bring together global leaders focused on the utilization of genetic resources and gain their perspectives on how to advance the value and usage of collections based on recent scientific progress in breeding, genetics, genomics, phenomics, data management, and related disciplines.

The Consultation: We would like to undertake this consultation to address the following topics related to recent advances in the sciences of breeding, genetics, and allied disciplines:

- A summary of cutting-edge science impacting how we think about populating, managing, enhancing, and using collections in the 21st century
- Feedback from users on ex situ collections in terms of accessibility, composition of collections, accession level information, etc.
- Input from users into the global needs for the long-term conservation and use
- Input from users on what should be improved to enhance conservation and distribution of research resources, tools, technologies, and methods
- Input on how to facilitate greater global collaboration and actions for scientific advancement and sharing of benefits from research and use of germplasm
- Highlight other critical issues for users in relation to strategic and effective and utilization of ex situ collections

Agenda

23 September

9:00-10:00A: P Bramel

Highlights of the 2007 global conservation strategy

- Summary of the 2021 collections survey
- Composition of the current ex situ collections
- Security of conservation for sorghum genetic resources
- Constraints to use of conserved genetic resources
- Key points for our subsequent discussions

Questions and discussion

Next sessions will be moderated by S Kresovich, input from all consultation participants

10:00-11:00A: Current ex situ collection status for conservation and use: global perspectives

- What are the metrics of a “good” collection?
- What’s working well in terms of composition of collections, accessibility of collections, accession level information, or the application of new tools?
- Where are the significant gaps or areas in need of improvement?
- How do we enhance progress and engagement of collections and researchers/breeders?

11:00-11:15 Break

11:15-12:00P: Impacts of key scientific advancements on future sorghum conservation and use

- Opportunities?
- Challenges?
- What do curators need to know?
- How do we help curators be successful to secure conservation and increase use?

12:00-13:00 Identification of global actions needed for the scientific advancement and sharing of benefits from research and use of germplasm

Goals?

- Roles and responsibilities?
- How do we maximize benefits for all?
- Next step for global efforts to link and enhance sorghum conservation and use

12:00A: Final comments and adjournment