Sorghum Vulnerability Statement
Sorghum and Millet Germplasm Committee
Fall 2020

1. Introduction to *Sorghum bicolor* (L.) Moench.
   1.1. Biological features and ecogeographical distribution

Sorghum [*Sorghum bicolor* (L.) Moench] is a widely adapted, genetically diverse C_4 tropical grass that is the fifth most important cereal crop worldwide, being primarily grown in the semi-arid regions of the tropics and sub-tropics. Sorghum was originally domesticated in the northeast quadrant of Africa approximately 8,000 years ago (Wasylikowa and Dahlberg, 1999) and these landrace varieties became a vital resource for the peoples of Sub-Saharan Africa, Asia and Latin America. In Africa and India, sorghum is often 3-4 meters tall and photoperiod sensitive, so that grain matures during low rainfall periods. Grower selection and evolutional created diverse sorghum and pearl millet types that can be used for various food products, fodder, fuel and building material that are adapted to a wide array of environmental conditions, most notable drought and poor fertility. These drought tolerance characteristics included aggressive rooting and tillering, dormancy under stress, leaf rolling and stay green in sorghum and tillering and dormancy traits in pearl millet. Such characteristics allow sorghum to be grown successfully in areas considered to dry and nutritional poor for maize [*Zea mays*] and it occupies important ecological zones between wetter areas suitable for maize or rice and drier areas where wheat, rye and barley are more suitably adapted.

The first recorded evidence in sorghum in the United States comes from a letter written by Benjamin Franklin in 1757 to Samual Ward explaining how to grow and the benefits of broomcorn, a type of sorghum; however, it is thought that sorghum was in the US and the Americas much earlier than this having been introduced with slavery to the area. In the US the early introductions of sweet sorghums and guinea corn types from Africa allowed seedsmen and farmers to select varieties with superior agronomic traits and varying maturities and sorghum. In the 1930's and 1940's selection of mutations with 2 or 3 dwarfing genes allowed sorghum to be adapted to mechanical harvesting and these grain sorghum types were widely grown across widely across arid areas of the US and peaked at 26.7 million acres in 1957. The discovery of cytoplasmic male sterility in the 1950s enabled the development of a hybrid sorghum industry and commercially produced sorghum hybrids are primarily grown in the United States, Mexico, Australia, Argentina, Southern Europe and South Africa. Hybrid sorghums expressed a number of desirable traits including hybrid vigor for growth habit, higher yields, both grain and forage, greater uniformity and earlier maturity. Hybrids are found in all types of sorghum from grain, to hybrid sudangrass, silage, sweet and biomass sorghums. Most hybrids are bred to fit mechanized agricultural techniques, so yield, standability, uniformity and stability of production are key characteristics selected by commercial plant breeders. Host plant disease and insect tolerance are also part of this hybrid mix.

   1.2. Genetic base of crop production

Sorghum is primarily a self-pollinated crop, though outcrossing can and does occur. Pearl millet is a highly cross-pollinated crop due to its protogynous nature. In most developing countries that rely heavily on these drought tolerant crops, plants are selected in fields for preservation of seed for planting and in-field variability can be enormous. In the US, hybrid sorghum and pearl millet both utilize cytoplasm male sterility and the A, B, and R line designation for maintaining and restoring fertility in the hybrids. This requires separate breeding programs to develop A-lines and R-lines that will produce commercially successful hybrids.

1.3. Primary products and their value (farmgate)

Sorghum grain is the only product for which acreage, yields and production are routinely reported, while some silage acreage and production are estimated. In the United States, planted acreage of sorghum for grain decreased from 7.3 million ha (18 million ac) in 1985 to a low of 2.1 million ha (5.3 million acres) in 2019. In 2020, 2.3 million ha (5.6 million acres) were planted. Over the last 10 years, an average of 2.6 million ha (6.4 million ac) within the US have been planted to sorghum. Yields have average between a low of 33,357 hg ha^{-1} (49.6 bu ac^{-1}) to a high of 52,389 hg ha^{-1} (77.9 bu ac^{-1}), primarily reflecting variations in rainfall patterns, since sorghum is typically grown as a rainfed crop. Average yields over the last 10 years have been 45,395 hg ha^{-1} (67.5 bu ac^{-1}). Prices have fluctuated from 1996 through 2019 primarily driven by demand for feed grains, the export market, and the demand for sorghum as a feedstock in the ethanol industry. NASS estimated grain prices to range from a low of $2.89 cwt in 1999 to a high of $11.1 cwt in 2012 with prices averaging $5.76 cwt over the last 25 years. It is far more difficult to calculate the value of hay, forage sorghum, biomass, and sweet sorghum types or to even estimate the acreage of these diverse types. Sorghum forage is reported by the USDA, but these numbers seem to be too small, given the number of seed sales that occur annually for forage sorghum. The USDA reported that in 2016 137,188 ha (339,000 ac) of forage sorghum was harvested at approximately 3.65 t ha^{-1} (11.9 t ac^{-1}). These numbers appear to be rather small based on conversations with forage producers and seed industry representatives.

1.4. Domestic and international crop production

1.4.1. U.S. (regional geography)

Being best adapted to drier climates, sorghum production is concentrated in the states of Kansas, Texas, Colorado, Oklahoma, and South Dakota (top 5 planted acres in 2018). These five states accounted for over 93% of the acres of grain sorghum planted in the United States (5.69 M acres), but there has been a increase in acreage across the Southern US in the states of Missouri, Georgia, North Carolina, Arkansas, Louisiana, and Mississippi since 2010 as growers have sought a solution to glyphosate tolerant weeds and to expand the coarse grain production in these areas. Sorghum is not a GMO crop and normal production practices use selective herbicides that provide control of broadleaf and grassy weeds. In most environments, sorghum is grown without supplemental irrigation or with limited irrigation compared to corn. A high yielding sorghum crop can be produced on approximately 2/3 of the water needed for maximum corn production, and likewise, with approximately 2/3 of the nitrogen fertilizer normally applied for optimizing corn yields

1.4.2. International

Sorghum world harvested acreage and production has remained stable through the most recent decade. Approximately 42.6 M ha (105 M acres) of sorghum are harvested annually (FAOSTAT, 2020) with production values of 59.3 MMT reported in 2018 from 111 reporting countries. Yields per hectare (acre), however, vary widely from 281,083 hg ha^{-1} (418.0 bu ac^{-1}) in Oman to less than 1,853 hg ha^{-1} (2.8 bu ac^{-1}) in Namibia. Worldwide average yields are a bit more realistic at 26,742 hg ha^{-1} (39.8 bu ac^{-1}). These wide discrepancies may be partially explained by the use of hybrids and intensive agricultural practices in developed countries while developing countries rely heavily on landrace varieties that are rainfed grown for specific food quality aspects or regional environmental adaptation. Five countries with the greatest production account for 50% of the world's total production with the United States, Nigeria, Sudan, Ethiopia and India accounting for the bulk of the production. Argentina, Australia and the United States provide most of the grain for export channels with Japan and Mexico traditionally being the primary importers; however, in recent years China has become an important importer of all sorghum. Additional information on acreage, production and consumption is available on the FAOStat website.

2. Urgency and extent of crop vulnerabilities and threats to food security

2.1. Genetic uniformity in the "standing crops" and varietal life spans

Genetic diversity within sorghum as grown in the United States is somewhat limited. Many hybrids have similar parentage and virtually all are produced using A_1 cytoplasm. The risks are serious enough that any one hazard could have a detrimental effect on many of the hybrids grown at any one time. One example is the impact that ergot, (*Claviceps africana*) had on commercial hybrid production areas after its introduction from Brazil in 1997. Since this pathogen attacks during flowering and is more infectious on sterile lines, it has forced production of some hybrids into new isolation areas where the disease is not present, such as California, Arizona and Washington where cost of production is significantly higher than traditional seed production regions. Hybrid lifespan in the United States is somewhat unpredictable, since the introduction of new hybrid combinations for all types of sorghum vary from year to year. As with most hybrid crops, from early identification to release to farmers typically ranges from between 8-12 years. A positive aspect of sorghum research is that private companies have diverse germplasm and skilled personnel who can quickly address problems which might arise. Although the crop being grown at any one time is rather uniform, considerable genetic diversity is available within breeding programs and could be deployed quickly if needed. This does not imply that we have identified the necessary diversity to address all of the problems that currently exist, much less those that might arise. We do not have germplasm with all desired traits identified nor is a systematic program in place to introgress traits into elite cultivars. To reduce or minimize the genetic vulnerability of the crop we must be sure that breeders, both public and private, have readily available to them diverse germplasm and adequate information about that germplasm so that they can fully exploit its potential and respond to current needs. The accessibility to and dispersion of information should be handled as much as possible through the NPGS system.

2.2. Threats of genetic erosion in situ

Sorghum faces considerable threats in terms of in situ preservation of important landraces and varieties with the introduction of improved varieties of other crops such as maize that are being planted on what had historically been sowed to millet and sorghum. This is reflected in the rather stagnant yields of sorghum in both Africa and India as traditional sorghum acres are replaced by maize and other non-adapted species for food production and sorghum is displaced to more marginal lands. Prior to the beginning of targeted collections of germplasm in the late 1950s, farmers were the primary curators of genetic diversity in these crops and these collections were maintained in situ. As new crop species were introduced to these farms, some of the genetic diversity of their traditional crops have been lost and/or replaced by other species. This remain a threat to in situ preservation of the two crop species. Wild sorghum collections are rather poor and it is extremely difficult to find wild populations in situ. Again, this is a reflection of rather aggressive herbicide and weed control programs that targeted weeds in farmer's fields and the loss of natural ecosystems, where these wild relatives may have once thrived.

2.3. Current and emerging biotic, abiotic, production, dietary, and accessibility threats and needs

Most common pathogens of sorghum have been widely distributed for some time. There are a few that have limited distributions and there are some that may be evolving as agriculture changes. For purpose of this analysis the following terms are presented: Seedborne pathogens are those that can be detected on, in or within the seed. Seed transmission implies that infected seeds are the means by which pathogens can be transmitted to plants grown from the seeds. (Denis C. McGee, 1988).

2.3.1. **Biotic (diseases, pests)**

Since sorghum produces a naked exposed grain many organisms are carried on seed. Some function as a means of disease dissemination. Diseases of greatest prevalence will be discussed. Discussion of pathogen herein does not necessarily mean that any would be of quarantine significance because many of these pathogens are cosmopolitan. For a more complete guide to sorghum diseases see the American Phytopathological Society's publication Compendium of Sorghum Diseases.

2.3.1.1. *Plant Diseases*: **Sorghum Downy Mildew**: *Peronosclerospora sorghi* Butler 1907. This pathogen has been extensively studied in relation to seed. The evidence indicates that oospores associated with the seed, as contamination in glume tissue or other leafy tissue, were obtained from infected plants or uninfected plants grown adjacent to affected plants. Oospores do not develop in seed. Mycelium of the downy mildew pathogen growing in seed during development is ineffective once the seed is dried. Recent changes in race structure in South Texas and Central Mexico highlight the dynamic nature of this pathogen as biotypes resistant to current fungicides and genetic resistance have occurred. **Anthracnose**: *Colletotrichum* *sublineolum* (Henn.) (formerly *C. graminicola* (Ces.) G.W. Wilson). It has been suggested that *Colletotrichum* isolates attacking johnsongrass represent a sibling species of the pathogen attacking sorghum (unpublished), while isolates of the pathogen attacking sorghum and maize are separate species (Vaillancourt and Hanau, 1992). **Ergot**: *Claviceps africana* Frederickson, Mantle and DeMilliano and *Claviceps. sorghi* Kulkarni, Seshadri & Hegde. These and related ergots of sorghum have caused considerable interest. *C. africana* has appeared in essentially all sorghum growing regions of the world in spite of strict quarantines. The evidence indicates that the pathogen is disseminated long distances in contaminated grain (Tooley et al., 2002) or as conidia carried in the atmosphere (Chakrabotry and Ryley, 2008). The fact that it is widely distributed reduces the significance of further quarantine. **Smuts**: Covered kernel smut *Sporisorium sorghi* (Ehrenberg ex Link) (= *Sphacelotheca sorghi* [Link] G. P. Clinton and Loose kernel smut *Spacelotheca cruenta* Syn. *Spacelotheca holci* Jackson (This pathogen can also be shoot infecting). The smuts have been controlled for several decades by common seed fungicides. Control of covered smut is essentially 100%; it is highly unlikely to be found in commercially cleaned and treated seed. Loose kernel smut, since it can be shoot infecting will occasionally occur in tillers of forages grown in proximity to a feral or wild *Sorghum* spp. with loose smut. The disease constitutes only a casual problem. Non-tillered plants are rarely affected and only when grown in association with existing inoculum from infected plants. **Leaf Blight**: *Exserohilum turcicum* Pass. Leonard and Suggs. Rarely, infected leaf material could be carried with the seed, but this avenue of transmission is unlikely. Leaf blight can be a problem on sorghum under ideal environmental conditions or if the sorghum lacks resistance. There are two levels of resistance, one that conditions a generalized form common in commercial grain sorghum hybrids, and another that conditions resistance at the hypersensitive level under most if not all environmental conditions. **Bacteria**: *Burkholderia andropogonis* (syn. *Pseudomonas andropogonis*). There has been some evidence to suggest that the pathogen can be seed transmitted but more likely it is seed borne and occasionally causes infection. Normally the disease is widely distributed, causes little economic damage even in unusually susceptible cultivars. **Other disease of limited importance or limited global distribution**: Gray leaf spot *Cercospora sorghi*; Ladder leaf spot *Cercospora fusimaculans* (See Plant Disease 71:759-760.); Oval leaf spot *Ramulispora sorghicola*; Rough leaf spot *Ascochyta sorghina*; Sooty stripe *Ramulispora sorghi*; Target leaf spot *Bipolaris sorghicola*; Zonate leaf spot *Gloeocercospora sorghi*; Long smut; striga.

Insects and Mites: Many of the more important insect and mite pests of sorghum are distributed worldwide and already occur in the United States. However, a few important arthropod pests of sorghum have more limited distribution, particularly in Africa, but constitute a potential threat to sorghum in the United States. The following is not a comprehensive list of arthropod pests of sorghum, but does comprise a list of potential invasive species that might pose an economic threat to sorghum production in the United States. For a comprehensive list of sorghum insects that impact the United States please see Managing Insects and Mite Pests of Texas Sorghum (https://extensionentomology.tamu.edu/files/2019/02/Managing-Insect-and-Mite-Pests-of-Texas-Sorghum-ENTO-085-2018.pdf) that provides a relatively comprehensive look at the major insects impacting the United States. **Sugarcane aphid**: *Melanaphis sacchari*. This insect was not considered a major pest of sorghum in the United States until 2013, when it became established in grain sorghum in Texas. Since that time, it has spread throughout most of the sorghum grain and forage growing regions of the United States and can cause significant yield and quality losses. Early heavy aphid infestations during the vegetative stage can lead to no or limited grain development and potentially plant death in susceptible sorghum hybrid. Banks grass mites *Oligonychus* pratensis and two spotted spider mites *Tetranychus urticae,* can infest sorghum in the drier regions of the United States when the plants experience prolonged drought stress. **Soil Insects**: Wireworms (Elateridae), false wireworms (Tenebrionidae), white grubs (Scarabaeidae), cutworms (Noctuidae), and southern corn rootworm (Chrysomelidae) are generally distributed worldwide and attack several other crops in addition to sorghum. No widespread outbreaks of any of these would be expected because the insects have limited mobility. **Leaf and Stem Insects**: Several aphid (Aphididae) species, especially greenbug and yellow sugarcane aphid, are major pests of sorghum; however, the most damaging species of these aphids are already widely distributed in the sorghum-growing areas of the United States. Other ubiquitous leaf and stem sorghum arthropod pests that occur in the United States including: chinch bug (Lygaeidae), fall armyworm (Noctuidae), flea beetles (Chrysomelidae), grasshoppers (Acrididae), Banks grass mite (Tetranychidae), sugarcane borer (Pyralidae), lesser cornstalk borer (Pyralidae), and sugarcane rootstock weevil (Curculionidae). **Several leaf and stem insects are potential pests but have limited distributions and do not occur in the United States**. **Panicle/Kernel-Feeding Insects:** three cyclic panicle/kernel feeding insects are observed in the southern United States on grain, forage and silage sorghum in recent years; they are: sorghum midge, *Contarinia sorghicola* (Cecidomyiidae), corn earworm, *Helicovera zea* (Noctuidae), and sorghum webworm, *Nola sorghiella* (Noctuidae). **Africa**: shoot bug, *Peregrinus maidus* (Delphacidae); spittle bug, *Poophilus costalis* (Aprophoidae); African nutgrass armyworm, *Spodoptera exempta* (Noctuidae); red-headed caterpillar, *Amsacta moloneyi* (Arctiidae); shoot fly, *Atherigona soccata* (Muscidae); spotted stem borer, *Chilo partellus* (Pyralidae); maize stalk borer, *Busseola fusca* (Noctuidae); pink borer, *Sesamia calamistis* (Noctuidae); termite, *Macrotermes bellicosus* (Termitidae); sugarcane aphid, *Melanaphis* sacchari. **India and Asia**: leaf weevil, *Myllocerus subfasciatus* (Curculionidae); red-headed hairy caterpillar, *Amsacta albistriga* (Arctiidae); Oriental armyworm, *Mythimna separata* (Noctuidae); spotted stem borer, *Chilo* spp. (Pyralidae); pink borer, *Sesamia inferens* (Noctuidae). **Panicle-Feeding Insects**: Many of the panicle-feeding insects are widely distributed and already occur throughout the sorghum-growing regions of North America. These include sorghum midge (Cecidomyidae), corn earworm and fall armyworm (Noctuidae), sorghum webworm (Nolidae), blister beetles (Meloidae), false chinch bug (Lygaeidae), leaf-footed bug (Coreidae), and southern, rice, and conchuela stink bugs (Pentatomidae). **The following panicle-feeding insects have limited distributions and do not occur in the United States. Africa and Asia**: panicle bugs, *Eurystylus immaculatus* and *E. oldi* (Miridae); earhead bug, *Calocoris angustatus* (Miridae); sap-sucking bug, *Dolycoris indicus* (Pentatomidae); sap-feeding bug, *Spilostethus* sp. (Lygaeidae); iridescent blue-green cotton bug, *Calidea dregii* (Pentatomidae); Bollworm, *Heliothis armigera* (Noctuidae); earhead webworm, *Nola analis* (Nolidae); blister beetle, *Mylabris pustulata* (Meloidae); armoured bush cricket, *Acanthoplus speiseri*. **India:** Christmas berry (earhead) webworm, *Cryptoblabes gnidiella*

(Pyralidae)**;** hairy caterpillar, *Euproctis subnotata* (Lymantriidae). **Stored Grain Insects:** Insect pests of stored grain generally infest a variety of grains and are typically cosmopolitan in distribution. The most important pests already occur in the United States and include: maize and rice weevils (Curculionidae), flat grain beetle (Cucujidae), confused and red flour beetles (Tenebrionidae), lesser grain borer (Bostrichidae), rice and Indian meal moths (Pyralidae), and angoumois grain moth (Gelechiidae).

2.3.2. **Abiotic**

Sorghum is one of the most drought tolerant cereal crops grown worldwide and research programs are currently underway to elucidate the genetic control of those drought responses within sorghum. Sorghum offers an ideal model crop for study, since it has a rather small genome, was the second major cereal crop to be sequenced and has a diverse and adaptable genomic structure. As climate change impacts weather and environmental conditions, sorghum is suited to be a more important cereal crops.

2.3.3. **Production/demand**

Production and demand have remained very consistent over the last 10 years with a shift in demand coming primarily from China, which replace Mexico and Japan as a major importer of sorghum. This was primarily driven by demands for non-GMO feed and the need to support their duck, , and distilled liquor industry. Demand for sorghum will continue to reflect historical end users of the past several years, with some potential growth in human and pet food industries as more domestic sorghum enters the gluten-free and ancient grain market.

2.3.4. **Dietary**

For an excellent review of sorghum nutrition please see http://www.simplysorghum.com.

2.3.5. **Accessibility**

Changes in support for public research and consolidations within the seed industry raise several concerns related to sorghum research and use of germplasm diversity. These concerns are: fewer and smaller public breeding programs; fewer scientists at the national level; a relatively local and narrow focus of public programs; a focus on molecular and laboratory training rather than field training; fewer private companies with limited resources for research investment; a narrow group of parental lines used within a given company; limited investment by either public or private in screening and incorporating exotic germplasm and issues raised by the Convention on Biological Diversity with its limitations on germplasm exchange. These issues will continue to affect the sorghum research community both nationally and internationally.

3. Status of plant genetic resources in the NPGS available for reducing genetic vulnerabilities.
   3.1. Germplasm collections and in situ reserves
      3.1.1. Holdings: Ninety-six percent of the collection is now backed up. Eighty-six percent of the collection at Griffin is now stored at -18º C. In 2015 a total of 14,898

samples of sorghum was distributed in 214 orders throughout the world. This represents about 6.6% of the total distributions within the NPGS.

3.1.2. Genetic coverage and gaps: The overall collection represents most of the diversity in sorghum with good coverage of the major races and most of the working groups in sorghum. Collections from Africa and robust, while collections from China remain very limited.

3.1.3. Regeneration: 96% of the collection has had germination tests completed. A small percentage of the collection has germination rates below 50%; however, it has been reported that accessions that don't have very high germination rates will continue to deteriorate in storage, so these numbers are valuable for establishing increases for maintenance. In most cases there are adequate seed numbers for robust distribution.

3.2. Associated information

3.2.1. Genotypic characterization data: Several research groups are genotyping various sorghum panels. There has been discussion about developing a standardized, centralized database to house this information. With the new tools and the amount of data being generated, there is tremendous need for a standard platform for this data and more importantly a long-term commitment to store this data for future research opportunities.

3.2.2. Phenotypic evaluation data: There are approximately 1.2 million phenotypic data points currently on the sorghum collection. Phenotypic characterization ranges from ADF to Manganese Toxicity tolerance. The ability to do phenotypic evaluation is complicated by the fact that roughly 85%+ of the collection is photoperiod sensitive and will not flower in temperate zones. A complete list of the phenotypic characters taken on the collection can be found at: https://npgsweb.ars-grin.gov/gringlobal/cropdetail.aspx?type=descriptor&id=69

3.3. Curatorial, managerial and research capacities and tools

3.3.1. Staffing: Staffing continues to be an issue for germplasm curation throughout the USDA-ARS. Dr. Melanie Harrison replaced Dr. Gary Pederson as Research Leader at the repository site in Griffin, GA. However, with the loss of Dr. Pederson and key personnel to retirement, the institutional knowledge around the curation of sorghum will take years to restore. There continues to be the need for a dedicated sorghum curator to be either located in the Puerto Rico or at Griffin whose primary responsibility will be the oversight of this complex germplasm collection. There is still much work that needs to be done in data collection and evaluation of the collection. Staffing continues to be a weak point within ARS for these types of collections.

3.3.2. Prior to Dr. Pederson's retirement, he and his staff worked to upgrade -18 storage and germination testing facilities at Griffin. The facilities, in general, are aging to the point that new facilities will be needed to upgrade the site.

3.4. Fiscal and operation resources: The NPGS continues to be underfunded and understaffed to support the huge diversity of plant and animal genetics that they are charged with curating and maintaining.

4. Other genetic resource capacities: The sorghum research community has grown in the past years because of the importance of sorghum in the Dept. of Energy's push toward more renewable forms of chemicals and energy. These groups include research partners that have been funded through the DOE's ARPA-e program. Each group is working on high-through-put phenotyping technology platforms to allow for greater phenotypic characterization of sorghum, which has been a limiting factor in much of the genomics research. Prior to these funding opportunities, the sorghum community had been working on various sorghum panels for genomic research activities and these remain active and widely used panels. The ARS has also developed a robust mutation library at their Lubbock facility that is providing valuable germplasm sources for both phenotypic and genomics work.

5. Prospects and future developments: New phenotyping and genomic tools will bring new capabilities to sorghum researchers to allow for greater exploration and exploitation of this world-wide important, drought tolerant cereal crop. Phenotyping technologies will allow for greater and more accurate field testing of new germplasm and allow for more efficient breeding of improved lines for hybrid and cultivar development. CRISPR gene editing offers extraordinary opportunities, especially in transforming photoperiod sensitive sorghum, which make up the bulk of international collections, into photoperiod insensitive collections that can then be grown and evaluated in temperate regions of the world. Currently, the sorghum conversion program takes from 5-8 years to convert sorghums and this could be significantly reduces, with greater conversion rates and true conversion of exotic parents.

6. References

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