FEED THE FUTURE
The U.S. Government's Global Hunger & Food Security Initiative

Feed the Future Innovation Lab for Collaborative Research on Sorghum and Millet

Annual Performance Report FY 2022

October 1, 2021 – September 30, 2022

USAID FROM THE AMERICAN PEOPLE

Collaborative Research on Sorghum and Millet
FEED THE FUTURE INNOVATION LAB

KANSAS STATE UNIVERSITY

Feed the Future Innovation Lab for Collaborative Research on Sorghum and Millet
Annual Performance Report FY 2022

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Cover photo:
Field days at Garin Mai gari - Madarounfa for F8 (MDKxL153-5) in Niamey, Niger
Photo credit: Ousseini Abdou Ardaly

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Management Entity Information

The management entity completed the fiscal year 2022 with the following staff members:

- Timothy J. Dalton, Ph.D. – *Director*
- Nathanael D. Bascom – *Assistant Director*
- Benjamin E. Kohl, Ph.D. – *Program Administrator*
- Kinzey J. Cott – *Fiscal Analyst*

External Advisory Board Information

Since the inception of the Feed the Future Innovation Lab for Collaborative Research on Sorghum and Millet (SMIL), the External Advisory Board (EAB) has played a key role in ensuring that SMIL's research and management practices are both high-quality as well as relevant. The EAB members have remained consistent throughout the life of SMIL. All original five members elected to continue their service into Phase 2, and are joined by our USAID Agreement Officer Representative, Dr. Faith B. Tarr.

1) Dr. Faith Bartz Tarr – *Agreement Officer Representative (AOR) at USAID*
2) Dr. Brhane Gebrekidan - *Ethiopian Academy of Sciences*
3) Dr. Bettina Haussmann - *University of Hohenheim, also serving as West Africa Liaison Scientist for the McKnight Foundation and Capacity Development Manager at the KWS SAAT SE*
4) Mr. Timothy Lust - *Chief Executive Officer of the National Sorghum Producers*
5) Dr. Peter Matlon - *Adjunct Professor at Cornell University*
6) Dr. Barbara Stoecker - *Regents Professor and Marilynn Thomas Chair at Oklahoma State University*

As in previous years, the SMIL management entity (ME) continued to provide periodic updates on activities and research-related developments to the EAB throughout the year, as well as consult them for guidance when areas of challenge arose.

The SMIL 2022 annual meeting was virtual (https://smil.k-state.edu/2022-smil-annual-meeting). The EAB provided valuable input to each project's representatives. The EAB found the format to be an effective way to discuss each project as we reviewed them one at a time. The online format also allowed for more in-depth discussion and reflections.

Focus Countries

SMIL continues to work primarily in its focus countries – Ethiopia, Senegal, and Niger – and secondarily in Burkina Faso, Togo, and Haiti, seen in Figure 1. For more information about focus countries, please visit the following webpages.
Ethiopia - https://smil.k-state.edu/ethiopia
Niger - https://smil.k-state.edu/niger
Senegal - https://smil.k-state.edu/senegal
Haiti - https://smil.k-state.edu/haiti

Figure 1 Sorghum and Millet Innovation Lab (SMIL) map of program activities and partners

List of Program Partners

United States of America

Colorado State University
Cornell University
Kansas State University
Kansas State University – Western Kansas Agricultural Research Center, Hays
Purdue University
Texas A&M AgriLife Research
Texas A&M University
USDA-Agricultural Research Service

Ethiopia

Amhara Agricultural Research Institute
Assosa Agricultural Research Center
Ethiopian Institute of Agricultural Research (EIAR)
Haramaya University
Hawassa University
National Agricultural Biotechnology Research Center
Mek'ele Agricultural Research Center
Oromia Agricultural Research Institute
SNNPR Bureau of Agriculture and Natural Resources Development
Tigray Agricultural Research Institute

Senegal

Centre d'Etudes Régional pour l'Amélioration de l'Adaptation à la Sécheresse (CERAAS)
Centre National de Recherche Agronomique (CNRA)
FAPAL (farmer organization)
Institut Sénégalais de Recherches Agricoles (ISRA)
Institut de Technologie Alimentaire (ITA)
University Cheikh Anta Diop de Dakar

Niger

Fuma Gaskiya (farmer organization)
Mooriben (farmer organization)
HALAL (farmer organization)
Institut National de la Recherche Agronomique du Niger (INRAN)
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)
LSDS (farmer organization)
University of Maradi

Burkina Faso
Institut de l'Environnement et de Recherches Agricoles (INERA)

Togo
Institut Togolais de Recherche Agronomique (ITRA)

Haiti
CHIBAS
Quisqueya University

Germany
University of Hohenheim

France
Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)

Acronyms

ARS	Agricultural Research Service
AOR	Agreement Officer Representative
ATI	Agriculture Transformation Institute
BMR	Brown Midrib
BMGF	Bill & Melinda Gates Foundation
CERAAS	Centre d'Etude Régional pour l'Amélioration de l'Adaptation à la Sécheresse
CGIAR	Consultative Group on International Agricultural Research
CHIBAS	Centre de Recherche sur les Biocarburants et l'Agriculture Durable
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
CNRA	Centre National de Recherche Agronomique
COVID-19	Coronavirus Disease of 2019
CSU	Colorado State University
CIMMYT	Centro Internacional de Mejoramiento de Maíz Y Trigo
DG	Directorate-General
EAB	External Advisory Board
ECC	Ethiopian Core Collection
EIAR	Ethiopian Institute of Agricultural Research
EMMP	Environmental Mitigation and Monitoring Planning
EMS	Ethyl Methanesulfonate
FPIL	Food Processing Innovation Lab
FY22	Fiscal Year 2022 (October 2021 – September 2022)
DNA	Deoxyribonucleic Acid
GBS	Genotyping-by-sequencing
GENMIL	Genetic Enhancement of pearl Millet
GoHy	Goal-Directed Hypothesis-Driven
GWAS	Genomic-wide Association Study
HX	Heterowaxy
HPD	High Protein Digestibility
ICRISAT	International Crops Research Institute for the Semiarid Tropics
IDIN	International Disease and Insect Nursery
IDLT	International Drought Line Test
ILCI	Innovation Lab for Crop Improvement
INERA	Institut de l'Environnement et de Recherches Agricoles
INRAN	Institut National de Recherches Agronomiques du Niger
IPM	Integrated Pest Management
ISRA	l'Institut Sénégalais de Recherches Agricole
ITA	Institut de Téchnologie Alimentaire
KSU	Kansas State University
KDA	Kansas Department of Agriculture
LICD	Local and Institutional Capacity Development
ME	Management Entity
MHM	Millet Head Miner
MLT	Midge Line Test
MSB	Millet Stem Borer
NAM	Nested Association Mapping
NARI	National Agricultural Research Institute(s)
NARS	National Agricultural Research System(s)
NSP	National Sorghum Producer(s)
OPV	Organic photovoltaic

OSU	Oklahoma State University
PI	Principal Investigator
PIL	Peanut Innovation Lab
PMP	Performance Monitoring Plan
QTL	Quantitative Trait Locus
R&D	Research and Development
R4D	Research for Development
RFA	Request for Application
SAWAGEN	Sorghum Adaptation in West Africa with a Genomics-Enabled Breeding Network
SICNA	Sorghum Improvement Conference of North America
SME	Small Medium Enterprises
SMIL	Sorghum and Millet Innovation Lab
SNP	Single Nucleotide Polymorphism
UAV	Unmanned Aerial Vehicles
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
WAAPP	West Africa Agricultural Productivity Program
WACCI	West African Centre for Crop Improvement
WX	Waxy

Glossary

Agglomerate: Process of creating food product balls, such as couscous
Anthracnose: A group of fungal diseases
Forage: Plant material consumed by livestock
Fortificant: Food additive to increase nutritional quality
Genomic enabled: Plant breeding selection process focusing on genetic markers
Genotyping: The process of determining genetic differences
Landrace: Traditional or local unimproved plant or animal
Lysimeter: A device that can measure evapotranspiration
Pathotype: A disease-causing variant of a microorganism
Phenotyping: Assessment of expressed traits in plants
Phylogeny: The evolutionary development and diversification of a species
Pleiotropic: Producing multiple effects from a gene
Smut: Fungal disease
Stover: Leaves and stalks of a plant
Striga: Genus of a parasitic plant

Executive Summary

The Feed the Future Innovation Lab for Collaborative Research on Sorghum and Millet (SMIL) completed its ninth year during FY 2022. This is the fourth year of the second phase and a considerable number of new innovations continue to impact our stakeholder community.

In Ethiopia, there is widespread dissemination of the *Merera* OPV and large-scale demonstration of hybrid ESH4 and ESH5. A new white-seeded sorghum *Jabaa* OPV was approved for release this year and seed will be multiplied for dissemination in 2023. Consumer acceptance of injera made from mixtures of *Merera* with teff (at a ratio of 3:7) is very high and rivals 100% teff. These mixtures have the potential to significantly reduce the cost of production for injera, thereby increasing household economic resiliency through food expenditure savings. Additionally, disease host plant resistance of both *Merera* and *Jabaa* increase production resiliency by reducing yield loss under pest pressure.

This strategy towards enhancing resiliency is also successful in West Africa. Large scale promotion and outreach of the millet seedball technology stretches from eastern to western Niger. A caravan of promotion traveled throughout the nation to sensitize rural areas on the benefits of the seedball. Overall, and with many on-farm trials over several growing seasons, seed balls increase average pearl millet yield by nearly 20% and profitability only slightly less due to the low cost of production. Collaborating projects with the McKnight Foundation are now bundling the seed ball with other low-cost innovations. New sorghum and pearl millet varieties are in stage five and are being reviewed for release in early 2023 in Niger. An exciting development is that a simpler strategy for increasing host plant resistance against *Striga* and heat and drought stress was discovered by an early-career scientist from Niger. Six BMR sorghum forage varieties are entering phase five.

In Senegal, the sorghum and pearl millet teams are revolutionizing the plant breeding landscape through collaboration on consumer acceptance with ITA. Multiple high yielding sorghum varieties with resistance against grain mold are being evaluated for consumer palatability prior to their release in 2023. Only those with good organoleptic properties will be moved from stage five into stage six. The program is also developing numerous highly digestible protein lines that are in stage five and poised to move into release. Seven pearl millet varieties are now available for adoption, a new hybrid and one OPV are entering stage six while three additional ones are completing stage five.

Rural cooperatives are setting new records for income generation in Niger. The Hub and Spoke system led to new tertiary centers whose members have been trained by first generation spoke centers indicating the multiplier effect of information dissemination. Some of these centers are producing composite flours made from millet and peanut, plus additional food fortificants, that have higher consumer acceptance rates than maize-soybean blends commonly distributed by local health centers. Nutritional studies have been conducted in Senegal, and soon in Niger, to determine the potential for food-to-food fortification of traditional and new food products. The Sensory Evaluation Lab will open at ITA in Dakar in October 2022. This center will serve as a hub for food product evaluation as well as one that will evaluate sorghum and pearl millet grain quality properties of new varieties under development.

Focus Country Key Accomplishments

Ethiopia

Considerable effort is being invested in rolling out the *Merera* variety in several locations. Approximately ten tons of seed were multiplied for distribution in the targeted region. A second white seeded variety, *Jabaa*, was recently approved for official release that also contains resistance against pathogens and it is being multiplied for distribution in 2023. Unfortunately, civil unrest in these areas has made it difficult for travel, observation, and collection of on-farm performance data. Large scale demonstration (48 ha) of ESH4 and ESH5 hybrids were conducted in Oromia region. Certified (3.5 ha) and foundation (0.75 ha) seed of ESH4 and ESH5 hybrid were multiplied. The SMIL Management Entity (ME) sponsored a seed system retreat at Melkassa with participants from the public and private sectors from three countries. On the value-added product side, the Hawassa team developed standardized protocol for making injera from sorghum and teff. These protocols have been implemented for screening the different injera formulations by sensory panels. Local sorghum, improved sorghums and novel sorghum lines were tested for a potential replacement of teff in injera making. The screening was done based on trained panelist with 24 quality descriptors for injera. Sorghum added at <30% to teff and is essentially similar in injera making quality using 100% teff. There were nine students from Ethiopia pursing advanced degrees during the 2022 fiscal year.

Niger

A massive campaign to popularize the seed ball technology was conducted in the Maradi region. The campaign consisted of a caravan of vehicles, signage and audio to familiarize the broader population on the benefits of seedballs. Analysis of multi-year, multi-locational large-N trials indicate robust average increase in yields of 20% and that yield gains are larger in proportional terms on poor soils and under more austere growing conditions. Profitability advantages are nearly 20% due to the low cost of component elements even when the cost of labor is included.

The sorghum and millet breeding programs are preparing technical information for the evaluation and release of new sorghum varieties in 2023. These varieties are the products of past investment in *Striga* resistance, forage quality and heat and drought tolerance. Recently, the sorghum program demonstrated that heat and drought tolerance and the *Stay-green* QTL is collocated with *Striga* resistance, making it possible to introgress these two highly desirable traits at the same time thereby avoiding any negative effects of pyramiding these traits.

In Niger, five rural food processing centers (i.e. Spoke Food Innovation Centers) had the high sales and profits for fortified flour products with ~US$9,000 in profit on nearly $19,000 sales since 2020. Labor is not charged by the rural women's associations in the calculation. There was the first clear indication with sales data that rural Spoke Food Innovation Centers are spreading from "secondary" spokes to "tertiary" spokes, showing an organic spread of technologies and ability of rural women processors (i.e. associations) to have successful processing enterprises. In a new study, naturally fortified flour blends using improved sorghum varieties were better accepted in consumer tests in Niamey and rural Niger, than the control fortified corn and soybean porridge made at local government community health centers. This suggests that fortified sorghum flour blends prepared to local tastes could be used more in local nutrition feeding programs. There were 11 students from Niger pursing advanced degrees during the 2022 fiscal year.

Senegal

Investments in the SAWAGEN project are leading to significant achievements affecting sorghum productivity in Senegal, Niger, and affiliated nations. Grain mold has been a key constraint for Senegalese farmers and four varieties in stage 5 of the product lifecycle are being evaluated for release in 2023. These varieties are a product of a phenotypic assessment combined with marker-assisted selection. During FY22, each of the four candidate varieties have been subjected to a battery of food quality and consumer-acceptability assessments to avoid the pitfall trap of unacceptable organoleptic qualities. This will result in the release of new varieties that are both agronomically superior and have desirable end-use qualities for human consumption. Continued emphasis on increasing drought resistance has led to novel institutional relationships and collaborative research between physiologists, geneticists, plant breeders and food scientists. Multilocational trials of drought resistant materials will move materials from stage 4 into stage 5 of the product lifecycle framework in Senegal. The Protein Digestibility Lab established in Senegal is serving as a hub of activity to develop

sorghum cultivars with improved post-cooking protein digestibility. Initial efforts focused on incorporating the high lysine (hl) locus into locally adapted varieties. Several backcross introgression lines have been developed in Faourou (ISRA-S-621B), a farmer-preferred variety that integrates farmer preferences for seed size, color, cycle, and easy processing, producing an average yield of 2 t/ha, and greater than 60% post-cooking protein digestibility. Seeds of the of the best lines are being increased and were proposed for official registration in August 2022.

Outreach dissemination of new varieties was combined with continued development of new pearl millet varieties and hybrids in Senegal, where one and half tons of new varieties were distributed among 900 lead farmers, potentially reaching 7900 end-users in 2023. Fifty farmers were trained on seed production and multiplication in our community-based seed multiplication activities. A nutrition impact study was redesigned based upon the Food Processing Innovation Lab (FPIL), Senegalese diet market assessment study. The two-part study looks at potential changes in diet quality (with nutrition status implications) at rural spoke processing sites where nutrient-fortified flour blend products were introduced over the last years. Each survey study will take 3-4 weeks. In Dakar, the sensory testing center at ITA is finished and its inauguration is set for October 20, 2022. Incubation of youth entrepreneurs is growing at the Senegal incubators, based at ITA. There were 13 students from Senegal pursing advanced degrees during the 2022 fiscal year.

Research Program Overview and Structure

SMIL continues its established course with a few changes that are responsive to program evolution. The program currently has nine projects and funding commitments to 15 institutions. Projects are led by several institutions including Purdue University (four projects), Colorado State University (one project), Texas A&M (two projects), the Senegalese Institute for Agricultural Research (one project) and the University of Hohenheim (one project). The pearl millet improvement project is being led by the Senegalese national agriculture research program, the Senegalese Institute for Agricultural Research (ISRA), and integrates researchers from Burkina Faso, Niger, and Senegal. These projects are associated with 18 collaborating institutions in West Africa and another 16 collaborating institutions in Ethiopia, as well as one collaborating institution in France. Activities in Haiti, under an Associate Award, came to an end in fiscal year 2021 and follow-on activities have been funded by SMIL's core financial resources.

The SMIL research program is organized around three areas of inquiry: 1) Genetic enhancement, 2) Production systems management, and 3) Market development and added-value products. Since the program is commodity-focused, 63% of SMIL projects focus on sorghum and pearl millet crop improvement, 17% in production systems management, and 20% in added-value products. Geographically, slightly more than 35% of SMIL financial resources for research are focused on Ethiopia and the remainder in West Africa.

Theory of Change and Impact Pathways

Figure 2 illustrates the SMIL Theory of Change (ToC). A foundational starting point are the national needs assessments that documented the demand for research by SMIL in-country stakeholders/actors. Three areas of inquiry respond to those identified research demands and the SMIL global research network has had tangible output success in technology development/deployment, as well as long-term local capacity development. The SMIL program, over time and in close collaboration with national partners, is achieving three key program goals ultimately leading to a sustainable reduction in global hunger, malnutrition, and poverty.

- *Build a coalition of science and industry around sorghum and millet.*
- *Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet, thereby extending economic benefits beyond the farm gate into the broader population.*
- *Create an economically rationalized business and research investment plan to leverage USAID core financing and attract associate awards and broader donor support.*

The SMIL ME continues to facilitate diffusion of technology packages together with and our national partners through leveraging of other USAID investments and cultivating networks that support technology co-creation, dissemination, and end-user feedback.

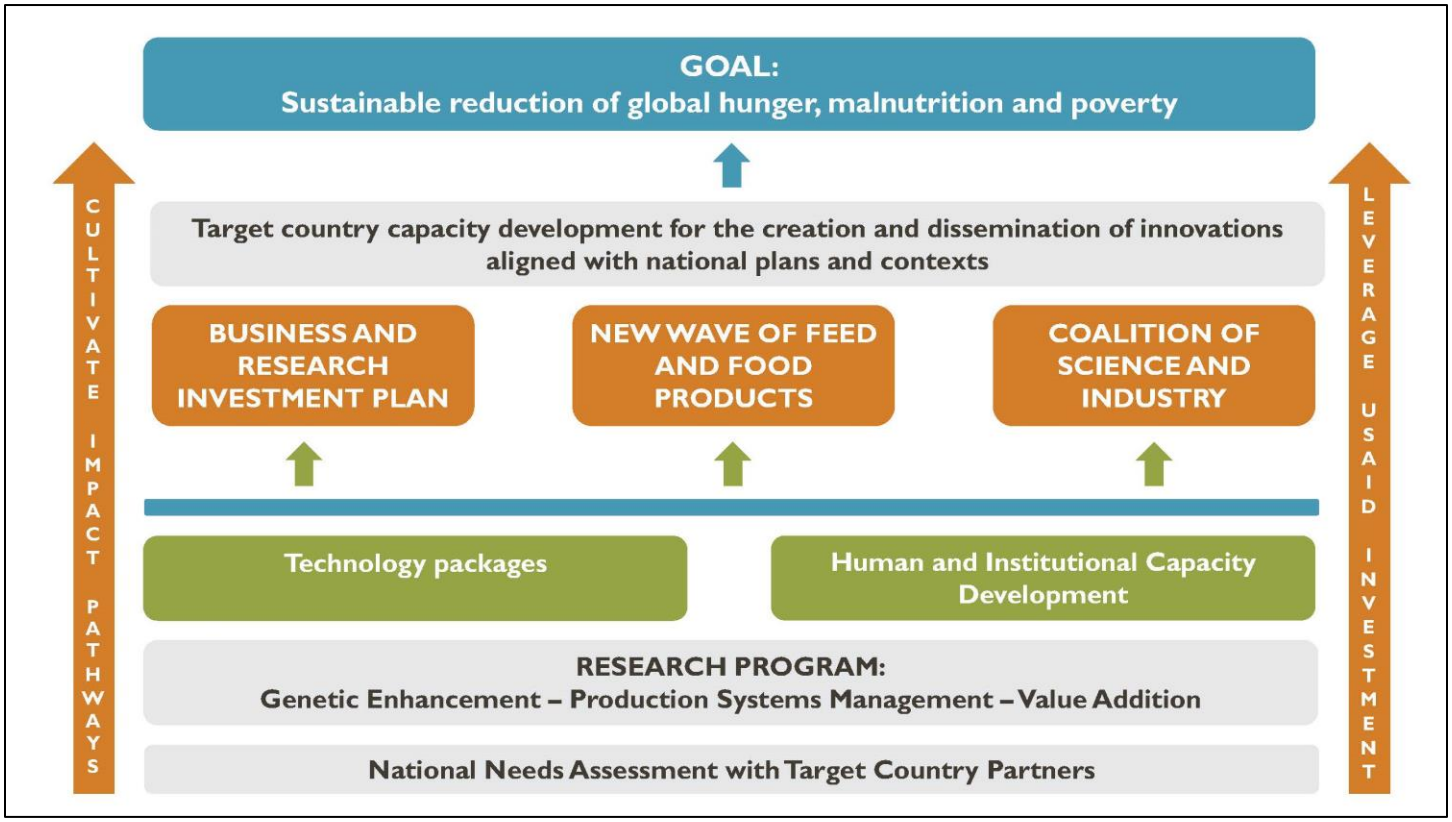


Figure 2 Sorghum and Millet Innovation Lab Theory of Change

The ToC embedded in the Sorghum and Millet Innovation Lab's activities is based on a "bottom up" approach of identification of needs and priorities derived from stakeholders along the sorghum and millet value chains. A competitive call for proposals was used to identify the innovative research projects to address these national identified needs.

Specific technology packages have been developed and there have been key successes in bringing them to a Phase 3 and Phase 4 level through multiple scaling pathways. The SMIL technology catalog is at https://smil.ksu.edu/smiltechnologies. The technology catalog features technology packages and there are multiple technologies listed in the USAID Research Rack Up database. The ME is also cultivating pathways to support uptake and scaling of technology packages. For example, SMIL allocated additional funds to support seed multiplication, farmer demonstration, and media promotion of the registered *Merera* disease-resistant sorghum to accelerate uptake in western Ethiopia.

Local capacity development is an essential cross cutting component of the SMIL's ToC. SMIL is building on the primary inputs into the innovation systems to include human capital in the form of stakeholders in product outcomes, trained and equipped research scientists, students, technicians, extensionists, technology transfer specialists, physical capital in the form of innovation centers, laboratories, farm and research station fields, other durable capital used to irrigate and cultivate fields, disposable supplies such as biochemical inputs, fuel and laboratory supplies, electricity, and internet/phone access. In addition, critical social capital found in producer groups and cooperative organizations contribute to familiarization, facilitation, and adoption of technologies.

Performance monitoring plan and the theory of change

Our performance monitoring plan defines key components to help measure progress towards our mission and links to the program's ToC. Our high-level goal is to contribute towards the sustainable reduction of global hunger, malnutrition, and poverty through a country-led development of innovative technologies that will be scaled along the sorghum and millet value chains as well as long-term local capacity development.

Our bottom-up approach is based on country-specific and robust support of national capacity and planning for research that is demand-driven. In-country research prioritization meetings provided the opportunity to develop a stakeholder analysis, discuss strengths and weaknesses, and discuss research constraints during the initial phase of program establishment. These meetings helped to lay a strong foundation for full integration into national-level priorities. The selected project design and objectives all contribute to these national and regional priorities to enhance and build upon current initiatives.

Local and Institutional Capacity Development (LICD) is also central to the SMIL ToC. At the national level, strategic support of existing forums to strengthen strategic planning and implementation and monitoring will be provided. Continued support to develop, mentor, and establish well rounded national research teams who have strong technical research capacities along with skills to present, package, and lobby are being achieved.

Ongoing stakeholder analysis is another aspect of our ToC to better understand the actors, their interests, and their power and influence in relation to the sorghum and millet value chains. Engagement with the key stakeholders such as policy actors, development partners, and end users is vital and cross-country learning has provided opportunities for engagement with multiple international actors.

The SMIL ToC also recognizes that development context, enabling environment and change is an extremely complex process with multiple actors, social, economic, and political factors, and cultural context. A strong mechanism for feedback, lessons learned, and planning adjustment is in place to consider alternative approaches or ways of thinking.

SMIL has continued to assess the risk assumptions at country/zone level. Together, with in-country coordinators and national team members, SMIL has embraced an "adaptive management" philosophy of finding mitigation strategies in response to stresses such as COVID-19, political instability, security threats, retention of staff, accelerated climate change, etc.

The SMIL ME continues to play an enabling role in development of global research teams that implement projects which are fully integrated into the national level research priorities. In addition to the long-term local capacity development outputs, technology packages are being co-created with end-users for further uptake. The SMIL ME is leveraging multi-sector collaborations and USAID investment to further scale these technologies.

Research Project Reports

Genetic improvement of sorghum for resistance to fungal pathogens

Led by
Dr. Tesfaye Mengiste
Purdue University - USA

Location (zonal level)
Ethiopia – East Shewa, North Wollo, Addis Ababa, Arsi, East Harerge, West Gojam, South Tigray, East Tigray

Description
The overarching goal of this project is to improve the livelihood of sorghum farmers in the plant disease prone regions of Ethiopia by providing disease-resistant and adapted varieties that also integrate other desirable traits. This project will build on scientific discoveries, disease-resistant germplasm, and networks of collaborators established in the first phase, to deliver genotypes that integrate critical traits including wide adaptation, disease resistance and high yield potential. Resistant genotypes identified through multi-year and multi-location field trials in the first phase of this project are already incorporated into the breeding pipeline of the national and regional research institutes. Introgression of disease resistance genes into widely adapted elite materials that are deficient in diseases resistance genes is also underway. These parallel efforts will be accelerated to complete the development and release of regionally or nationally adapted varieties that integrate important traits. To support sorghum improvement in the project target region and beyond, strategic research that focuses on gene discovery and scientific advances will be conducted through genetic and genomics studies of unique resistant materials and populations we developed. Genetic resources such as adapted landraces, breeding lines and recombinant inbred populations harboring resistance to foliar and grain disease were identified and characterized. Genes underlying these traits will be identified to develop molecular marker to support improvement of the crop in Ethiopia and other countries with similar challenges. A collection of Ethiopian sorghum landrace population was partially characterized, and genotype information generated. Deep phenotyping and sequencing of a core representative set of landraces, defined on the bases of genomic data, will be conducted to serve as the main source of traits for future breeding and strategic research, and lay the foundation for genomics enabled breeding platform. Finally, the project will incorporate graduate education, short term training and knowledge enhancing workshops to strengthen the human and institutional capacity of local research institutions.

Theory of change and impact pathways
All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet*. In addition, this project also supports *Objective II: Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet thereby extending economic benefits beyond the farmgate into the broader population*.

Collaborators

U.S. collaborating institution(s):	Purdue University, Kansas State University
Intl. collaborating institution(s):	*Ethiopia* - EIAR (Assosa Agricultural Research Center, Bako Agricultural Research Center), Oromia Agricultural Research Institute, Haramaya University

Achievements

Demonstration and popularization of *Merera* was conducted and seed increase (10 tons) was achieved. The primary success during the current reporting period is the approval and subsequent release of the white seeded sorghum variety *Jabaa*. This variety was approved for release by the national variety release committee. Further work in the coming year is required to increases seeds, and to conduct outreach and popularization activities. A short description of the variety is entered here. It is adapted to an altitude (masl) of 1500-1900 and rainfall of 1100-1200 mm. The variety is tolerant to major sorghum diseases (Anthracnose, grain mold, leaf blight, rust and smut) and bird attack. The variety shows high yield advantage of 39% over standard check variety and produces up to 4.2 tons/ha. Specifically, we observed a grain yield of 3.9-4.2 ton/ha on- station, and 3.5-3.8 ton/ha on farmer's field. It is early maturing and best fit for current climate change especially uncommon erratic rain fall. It has a relatively short stalk resistant to lodging and tolerant to grain and foliar diseases prevalent in the region. The variety is resistant to bird attack, and it is preferred by sorghum producers and consumers for making 'injera' and local homemade drinks.

A number of additional achievements include Variety Verification Trial (VVT): early maturing type and two candidate varieties in VVT with standard check (Bonsa) producing a yield advantage: 43.1, 39.1%, respectively. This occurred in Bako, Gute, Bilo boshe, Chawaka and Uke. The Technical committee evaluated these varieties and we are waiting decisions on official release and registration. Meanwhile introgression of traits into adapted and improved varieties and evaluation of segregating populations from crosses between resistant and other improved varieties are being evaluated. A total of F2:68 crosses generated 64 segregants that were promoted. Evaluation of F4 segregating population produced 132 F4 families evaluated in the 2021 cropping season and 65 lines with better diseases resistance promoted to next generation • Evaluation of F6 sorghum lines. Adapted varieties (Lalo, Gemedi and Geremew) were crossed with ETSL100375, PML981475, and SC283-14 to combine their desirable traits and 23 of the best promoted to yield trial (PYT) for further evaluation.

Capacity building

Individuals trained under this project include:

12	Haramaya University	Ph.D.	Plant pathology
39	Purdue University	Ph.D.	Plant pathology
80	EIAR, Assosa Research Center	Ph.D.	Plant pathology

Lessons learned

The major lesson is that due to the high turnover of staff, and the security issues in the country, a layer of back up support is required to accomplish projects. Despite this stress, the Ethiopian national and regional research institutions, and the sorghum improvement program has shown high a level of resilience in conducting the project. The SMIL investment in the characterization of the core germplasm has yielded varieties that have recently been approved by the national variety release committee and serves as a major source of traits for sorghum improvement.

Presentations and publications

Liao, C. J., Hailemariam, S., Sharon, A., & Mengiste, T. (2022). Pathogenic strategies and immune mechanisms to necrotrophs: Differences and similarities to biotrophs and hemibiotrophs. *Current Opinion in Plant Biology*, *69*, 102291. https://doi.org/10.1016/j.pbi.2022.102291

Lee, S., Fu, F., Liao, C. J., Mewa, D. B., Adeyanju, A., Ejeta, G., & Mengiste, T. (2022). Broad-spectrum fungal resistance in sorghum is conferred through the complex regulation of an immune receptor gene embedded in a natural antisense transcript. *The Plant Cell*, *34*(5), 1641-1665. https://doi.org/10.1093/plcell/koab305

Mewa, D. B., Lee, S., Liao, C. J., Souza, A. M., Adeyanju, A., Helm, M., & Mengiste, T. (2022). ANTHRACNOSE RESISTANCE GENE2 confers fungal resistance in sorghum. *BioRxiv*. https://doi.org/10.1101/2022.06.24.497546

Dessalegn, K., Lule, D., Nida, H., Mekbib, F., Girma, G., & Mengiste, T. (2022). Evaluation of selected Ethiopian sorghum genotypes for resistance to anthracnose. *European Journal of Plant Pathology*, *162*(1), 79-91. https://doi.org/10.1007/S10658-021-02386-6

Birhanu, C., Girma, G., & Mengiste, T. (March 2022). Genetic Improvement of Sorghum for Resistance to Fungal Pathogens. Presentation at SMIL Annual Conference, Virtual.

Genetic enhancement of sorghum to promote commercial seed supply and grain market development in Ethiopia

Led by
Dr. Gebisa Ejeta
Purdue University - USA

Location (zonal level)
Ethiopia – East Shewa, North Wollo, Addis Ababa, Arsi, East Harerge, West Gojam, South Tigray, East Tigray

Description
Ethiopian sorghums have been a great source of novel genes and valuable traits for improving the sorghum crop worldwide. Modern sorghum breeders have heavily relied on the natural diversity in sorghum landraces in search of useful traits in advancing sorghum as a feed crop in major economies, particularly in the Americas and Australia. Unfortunately, sorghum improvement in Africa lags far behind the successes that the crop has enjoyed in these other geographies. It is possible that modern research advances made on sorghum improvement in these advanced economies may benefit current and future sorghum research efforts in Africa.

This project proposes to employ tools of biotechnology, breeding, and agronomy to unleash the potential of the crop for needy farmers. They will work as members of a team in developing a core-set of sorghum germplasm population to characterize the inherent variability through genotyping by sequencing. The team will couple that with phenotyping of valuable traits under target environments and treating data with appropriate bioinformatics and statistical procedures to identify useful allelic variations for drought and *Striga* resistance. They will develop local capacity and restore rigor and discipline to the Ethiopian sorghum breeding program to produce superior sorghum cultivars on a regular basis.

The project aims to develop a functional sorghum breeding program in Ethiopia focused on the development of adapted, high yielding sorghum hybrid cultivars for broad societal impact. They will promote the use of hybrid cultivars to strengthen the seed supply value chain and catalyze the development of a commercial sorghum seed enterprise system in the country. Building a commercial value chain system for sorghum in Africa is among the most badly needed investments in Africa.

Theory of change and impact pathways
All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet.* In addition, this project also supports *Objective II: Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet thereby extending economic benefits beyond the farmgate into the broader population.*

Collaborators

U.S. collaborating institution(s):	Purdue University, Kansas State University
Intl. collaborating institution(s):	*Ethiopia* - Ethiopian Institute of Agricultural Research (EIAR), (Melkassa Research Center, Sirinka Research Center), Holleta Biotechnology Center, Tigray Regional Program, Oromia Regional Program, Haramaya University

Achievements
Drought response data on a subset of 358 Ethiopian sorghum landraces was combined with GBS data from phase I to conduct a GWAS for drought tolerance. Significant QTLs were not detected in the analysis, but drought tolerant landraces that can be used for drought breeding were identified. Towards our aim of establishing heterotic pools among

Ethiopian sorghum landraces, a large set of 322 hybrids of Ethiopian sorghum landraces were evaluated. This has generated evidence on heterotic responses of the landraces. Yield potential of different hybrid combinations were investigated we were able to see a tendency of some of the non-conventional hybrid combinations resulting in greater heterosis for grain yield than the conventional hybrid combination. Combining ability of landraces determined which showed some of the familiar landraces as top combiners that can be used in hybrid breeding program.

With the aim to develop improved parental lines for a hybrid program from Ethiopian landraces, significant progress was made in generating breeding populations with enhanced drought tolerance and other traits. A set of 176 F3 families of BxB cross populations advanced for conversion into first generation of sterile versions of the B landraces. This has resulted in 285 sterile counterparts of the landrace B lines. Similarly, we made good progress in R lines development based on native germplasm. From crosses and generation advances conducted during the reporting period, 149 R by R cross populations were generated and advanced into F2 stage. Cultivars selected as drought tolerant and dual purpose (grain and forage type) hybrids that surpassed the performance of check hybrids by up to 25% in grain and biomass yield, respectively were identified for a final stage evaluation for release consideration. Large scale demonstration (48 ha) of ESH4 and ESH5 hybrids were conducted in Oromia region. Certified (3.5 ha) and foundation (0.75 ha) seed of ESH4 and ESH5 hybrid multiplied.

Capacity building

Individuals trained under this project include:

44	Purdue University	Post-doctoral studies	Plant breeding and pathology
68	Purdue University	Post-doctoral studies	Plant genetics

Lessons learned

The conflict in Northern Ethiopia has disrupted research and development activities in Tigray and Amhara regions. Continuous discussions and consultations with the research team at the national program and regional staff helped to keep project activities running under very difficult conditions. Key lesson learned was the importance of peace and stability.

Presentations and publications

Ejeta, G. & Chikssa, H. N. (March 2022). Genetic Enhancement of Sorghum to Promote Commercial Seed Supply and Grain Market Development. Presentation at SMIL Administrative virtual meeting, Virtual.

Lee, S., Fu, F., Liao, C. J., Mewa, D. B., Adeyanju, A., Ejeta, G., & Mengiste, T. (2022). Broad-spectrum fungal resistance in sorghum is conferred through the complex regulation of an immune receptor gene embedded in a natural antisense transcript. *The Plant Cell*, *34*(5), 1641-1665. https://doi.org/10.1093/plcell/koab305

Chikssa, H. N. (2021). *GENETIC RESISTANCE TO FUNGAL PATHOGENS IN SORGHUM [SORGHUM BICOLOR (L.) MOENCH]* (Doctoral dissertation, Purdue University Graduate School).

Improving Sorghum Adaptation in West Africa with a Genomics-Enabled Breeding Network (SAWAGEN)

Led by
Dr. Geoffrey Morris
Colorado State University - USA

Location (department level)
Niger – Aguie, Bkonni, Kollo, Niamey, Tillabéri, Say
Senegal – Thies, Bambey, Tambacounda

Description
Despite some important successes in sorghum breeding in West Africa, the overall impact of sorghum improvement has not yet met stakeholder expectations on varietal adoption, increased farm income, or improved nutritional status. SAWAGEN brings existing R&D capacity together into a network to regularly deliver sorghum varieties that are adapted to West African environments, adopted by smallholder farmers, and appreciated by value-chain actors.

The SAWAGEN network brings together NARS breeders, NARS researchers, international collaborators, and farmer organizations. To align missions and leverage expertise among diverse scientists and stakeholders, we use a goal-directed hypothesis-driven (GoHy) method for program planning and adaptive management. At the core of the network are four early-career NARS breeders in Senegal (ISRA), Burkina Faso (INERA), Togo (ITRA), and Niger (INRAN), who were trained in genomics-enabled breeding during phase-I (SMIL and/or WACCI).

SAWAGEN's top priority is to develop new versions of locally preferred varieties that carry stress-resilience traits by the project's end in 2023. Each NARS breeder has identified 2–3 product concepts that will be delivered to smallholders within a 5–10-year time frame. The varieties will be under testing in farmers' fields - in partnership with farmer organizations - by 2023. SAWAGEN's other major product is the R&D network itself, with four platforms designed to scale beyond the current participants and beyond the end of the project.

Varietal development will be carried out in the Local Adaptation Breeding Platform with marker-assisted backcross of known stress tolerance alleles into locally preferred varieties and participatory evaluation. The foundation for delivery of future products will be laid with the Broad Adaptation Breeding Platform (gender-responsiveness training, germplasm exchange, recurrent population development, multi-environment trials); the Genetic Mapping Research Platform (genome-wide marker discovery, genetic mapping, marker development); and the Physiological Mapping Research (trait discovery, trait validation, ideotype definition).

Theory of change and impact pathways
All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet*. In addition this project also supports *Objective II: Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet thereby extending economic benefits beyond the farmgate into the broader population* as well as *Objective III: Create an economically rationalized business and research investment plan to leverage USAID core financing and attract associate awards and broader donor support.*

Collaborators

U.S. collaborating institution(s):	Colorado State University
Intl. collaborating institution(s) :	*Senegal* - Institut Sénégalais de Recherches Agricoles (ISRA), Centre d'Etudes Régional pour l'Amélioration de l'Adaptation à la Sécheresse (CERAAS), Centre National de Recherche Agronomique (CNRA)

Niger - International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Institut National de la Recherche Agronomique du Niger (INRAN), LSDS (farmer organization), HALAL (farmer organization)
Burkina Faso - Institut de l'Environnement et de Recherches Agricole (INERA)
Togo - Institut Togolais de Recherche Agronomique (ITRA)
France - Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)

Achievements

Investments in the SAWAGEN project are leading to significant achievements affecting sorghum productivity in Senegal, Niger, and affiliated nations. Grain mold has been a key constraint for Senegalese farmers and four varieties in stage 5 of the product lifecycle are being evaluated for release in 2023. These varieties are a product of a phenotypic assessment combined with marker-assisted selection. During this year, each of the four candidate varieties have been subjected to a battery of food quality and consumer-acceptability assessments to avoid the pitfall trap of unacceptable organoleptic qualities. This will result in the release of new varieties that are both agronomically superior and have desirable end-use qualities for human consumption. In Niger, the program on integrating host plant resistance against *Striga* is nearing the release of new varieties that have integrated *Striga* anti-germination properties of SRN-39 into locally preferred varieties. Most importantly, and what has not been done in the past, the program rigorously tested the achievement of the *Striga* resistance strategy in pots and in the field through complementary investment from the allele mining project funded by the Bill and Melinda Gates Foundation and the Lasky Lab at Penn State University.

Continued emphasis on increasing drought resistance has led to novel institutional relationships and collaborative research between physiologists, geneticists, and plant breeders. Multilocational trials of drought resistant materials will move materials from stage 4 into stage 5 of the product lifecycle framework in Senegal. An exciting and unexpected scientific discovery was found through the regional collaborative network. Using the *Striga* resistance trial in Niger, Dr. Maïna and collaborators determined that the mutant alleles in the LGS1locus that confers anti-germination of *Striga* collocate with stay-green thus providing a single pathway to improve *Striga* and drought resistance. Previously, pyramiding these two traits was the strategy, but this discovery will minimize the potential transfer of inferior or yield-dragging traits.

Capacity building

Individuals trained under this project include:

70	Universite Abdou Moumouni Niamey	Ph.D.	Crop Physiology
71	Universite Abdou Moumouni Niamey	Ph.D.	Crop Physiology
72	Colorado State University	Ph.D.	Plant breeding and genetics

Lessons learned

Human and institutional capacity building development is leading to globally and locally important scientific discoveries. Mentoring of students who have become young-professionals, and devolving leadership responsibility to these individuals, is creating conditions that will lead to sustainable locally led interdisciplinary research for development tackling some of the most wicked problems facing plant improvement in West Africa.

Presentations and publications

Maïna, F., Harou, A., Hamidou, F., & Morris, G. P. (2022). Genome-wide association studies identify putative pleiotropic locus mediating drought tolerance in sorghum. *Plant direct*, *6*(6), e413. https://doi.org/10.1002/pld3.413

Lasky, J. R., Josephs, E. B., & Morris, G. P. (2022). Genotype–environment associations to reveal the molecular basis of environmental adaptation. *The Plant Cell*. https://doi.org/10.1093/plcell/koac267

Faye, J. M., Akata, E. A., Sine, B., Diatta, C., Cisse, N., Fonceka, D., & Morris, G. P. (2022). Quantitative and population genomics suggest a broad role of stay-green loci in the drought adaptation of sorghum. *The Plant Genome*, *15*(1), e20176. https://doi.org/10.1002/tpg2.20176

Diatta, C., Mamdou, A., Akata, E., Ouedraogo, N., Sine, B., Hamadou, F., Fonceka, D., & Morris, G. (March 2022). SAWAGEN: Improving Sorghum Adaptation in West Africa with a Genomics-Enabled Breeding Network. Presentation at SMIL Administrative virtual meeting, Virtual.

Muleta, K., Felderhoff, T., Winans, N., Walstead, R., Charles, J.R., Armstrong, J.S., Mamidi, S., Plott, C., Vogel J.P., Lemaux, P.G., Mockler, T.C., Grimwood, J., Schmutz, J., Pressoir, G., & Morris, G.P. (2022). The recent evolutionary rescue of a staple crop depended on over half a century of global germplasm exchange. *Science advances*, *8*(6), eabj4633. https://doi.org/10.1126/sciadv.abj4633

Sorghum Trait Deployment Pipeline for Improved Food and Feed Value

Led by
Dr. Mitchell Tuinstra
Purdue University – USA

Location (department level)
Niger - Aguie, Bkonni, Kollo, Niamey, Tillabéri, Say
Senegal – Thies, Bambey

Description
This proposed project expands the team's sorghum crop improvement efforts through targeted research and technology transfer to promote and enhance sorghum production and nutritional value. Researchers have already identified allelic variation in genes that influence grain and forage quality; specifically, grain protein digestibility, modified starches that produce new functional food and nutritional attributes, and improved forage quality.

The Protein Digestibility Lab established in Senegal will serve as a hub of activity in West Africa for efforts to develop sorghum cultivars with improved post-cooking protein digestibility. As new varieties are developed, ISRA will engage with sorghum farmers and end-users to evaluate the bread-making and couscous-making qualities of grain produced using these varieties as well as their feed value in poultry rations.

A Forage Sorghum Breeding Program will be established at the INRAN Kollo Research Station. The bmr6 and bmr12 alleles will be used to develop new forage varieties in the El Mota and SEPON82 backgrounds. Hybrid forage varieties will be developed using locally adapted seed and pollinator parents. AN223 and selected A-lines from the breeding program will be crossed with elite forage and Sudan grass pollinators being developed at Purdue.

The crop development activities described in this proposal will produce new and unique sorghum varieties and hybrids with enhanced food- and feed-quality traits. Farmer participation during evaluation and selection of the best new varieties will promote acceptance and production of new cultivars. Researchers will also work with seed system specialists to encourage and enable seed production and distribution. Increased production and availability of high-quality seeds and grains will stimulate and support the development of new markets.

Theory of change and impact pathways
All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet*. In addition this project also supports *Objective II: Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet thereby extending economic benefits beyond the farmgate into the broader population* as well as *Objective III: Create an economically rationalized business and research investment plan to leverage USAID core financing and attract associate awards and broader donor support.*

Collaborators

U.S. collaborating institution(s):	Purdue University
Intl. collaborating institution(s) :	*Senegal* - Institut de Technologie Alimentaire (ITA), CERAAS, ISRA, CNRA *Niger* - INRAN

Achievements

The Protein Digestibility Lab established in Senegal is serving as a hub of activity to develop sorghum cultivars with improved post-cooking protein digestibility. Our initial efforts focused on incorporating the high lysine (hl) locus into locally adapted varieties. Several backcross introgression lines have been developed in Faourou (ISRA-S-621B), a farmer-preferred variety that integrates farmer preferences for seed size, color, cycle, and easy processing, producing an average yield of 2 t/ha, and greater than 60% post-cooking protein digestibility. Seeds of the of the best lines are being increased and were proposed for official registration in August 2022. Parallel genetic research studies have identified other genes that enhance protein digestibility. Two new mutant genotypes with enhance protein digestiblity were discovered including mutations in a disulfide isomerase and a kafirin storage protein. Genetic markers have been developed for these alleles to support introgression into locally adapted cultivars. These markers were transferred to the laboratory at CERAAS for validation in breeding populations. Other accessions with highly digestible protein were discovered in the native gene pool. Genome wide association studies identified genes contributing to these phenotypes.

The forage breeding program founded in Niger by Ousmane Seyni Diakiteis moving materials through the product lifecycle. Brown-midrib (bmr) traits for improved forage quality are being introgressed into locally adapted sorghum varieties. Elite parent lines and breeding populations from the U.S. are also being transferred to Niger to support the program. Improved lines with good forage quality and production attributes were identified in multi-location trials. Seeds of the of the best lines are being increased and seven new varieties will be proposed for registration after the fall harvest season. Agronomic studies are being conducted to identify and demonstrate best management practices.

Capacity building

Individuals trained under this project include:

73	University Cheikh Anta Diop	Master's	Plant and microbial biotechnology
79	University Cheikh Anta Diop	Master's	Plant and microbial biotechnology

Lessons learned

This proposed research, training, and capacity building project attempts to address key sorghum crop improvement needs through targeted research, short- and long-term training and education, and technology transfer to promote and enhance sorghum production. Key lessons from our research programs include: 1. Introgression of highly digestible protein (HDP) traits into locally-adapted and farmer-approved varieties improves farmer perception of the technology; 2. Newly discovered HDP traits represented by mutations in the disulfide isomerase and kafirin storage protein genes are unique and valuable for long-term crop improvement; 3. Some local sorghum accessions from Niger and Nigeria exhibited protein digestibility nearly as high as some of the genetic mutants discovered in this project; 4. Farmers readily accept new forage sorghum varieties with bmr traits; 5. Animal feeding studies that showed the great potential of bmr stover over conventional farmer varieties.

Presentations and publications

Diatta-Holgate, E., Hugghis, E., Weil, C., Faye, J. M., Danquah, A., Diatta, C., & Tuinstra, M. R. (2022). Natural variability for protein digestibility and grain quality traits in a West African Sorghum Association Panel. *Journal of Cereal Science*, 103504. https://doi.org/10.1016/J.JCS.2022.103504

Tuinstra, M.R., Diakite, S.O., Diatta, C., & Diatta-Holgate, E. (March 2022). Sorghum Trait Deployment Pipeline for Improved Food and Feed Value. Presentation at SMIL Administrative virtual meeting, Virtual.

Seed balls - Enhancing yield effect in pearl millet and sorghum and disseminating the technology in West Africa

Led by
Dr. Ludger Herrmann
University of Hohenheim – Germany

Location (department level)
Niger - Aguie

Description
Pearl millet farmers in Senegal and Niger face many challenges related to crop production, one of which is seedling survival. Technologies that enhance seedling survival in the Sahel present the potential of an important contribution to reduce overall cropping risks in the region, thereby enhancing pearl millet productivity and yield stability.

The project builds on the previous activities in phase-I to pursue the seed ball technology as a valid option to reduce cropping risks and improve farmers' yields - particularly for female farmers - by using low-cost resources that are readily available. The team continues to refine develop and dissemination of the seed ball technology in Niger. The research component addresses application to sorghum and combination with other yield enhancing innovations (e.g., fertilizer-micro-dosing). The development aspect is focused on mechanization of the seed ball construction process. Dissemination is based on collaboration with farmer federations (Fuma Gaskiya, Mooriben) in Niger. The latter is accompanied by a research component that surveys adoption pre-requisites and constraints.

Theory of change and impact pathways
All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet.* In addition, this project also supports *Objective III: Create an economically rationalized business and research investment plan to leverage USAID core financing and attract associate awards and broader donor support.*

Collaborators
Intl. collaborating institution(s): *Niger* - INRAN, Fuma Gaskiya (farmer organization), FUGPN Mooriben (farmer organization)

Achievements

The three years of on-farm trial series with hundreds of plots every year was finalized. Results were summarized in a scientific paper which allowed precise recommendations where to use the seedball technology. For instance, the effect fades out where a baseline panicle yield of one ton per hectare is reached, Thus, the relative effect of the seedball technology is decreasing with absolute yield level. In other words, it should be applied only on chemically infertile soil and in subsistence agriculture, where mineral fertilization is rare. The effect of the technology depends on the local soil types. In 2022 variants based on organic manure were tested.

The social science research revealed that seedballs are an adapted and adopted technology in the Maradi region of Niger. It has a low risk of loss on investment. Economic evaluation shows that the included communities in seedball research correspond to the general statistical composition of the population in that region. That way, the research results are representative and the technology shows an average yield gain of about 20%. In addition, the seedball technology was successfully transferred to the Falwel region in Niger but could not be sufficiently supported in the Tera region due to corona and security issues. Combined and supported research on seedballs in other projects of the involved partners revealed that seedballs can be successfully combined with another innovation called OGA (fermented human urine). While seedballs support the establishment phase, OGA supports further biomass production in later stages. An additional greenhouse trial at the University of Hohenheim showed that application of the seedball technology compensated for the negative biomass effects of seeds with low thousand grain weight. The master thesis of Achim Jesser on the development of the seedball mechanization prototype was awarded the Hans-Ruthenberg-Award at the University of Hohenheim.

Capacity building

Individuals trained under this project include:

53	University of Hohenheim	Master's	Soil science/Agronomy
54	University of Hohenheim	Post-Doctoral studies	Soil science/Agronomy
74	University of Hohenheim	Master's	Agritropics
81	University of Hohenheim	Master's	Agricultural Engineering

Lessons learned

There are three major lessons learned. 1. The social science research report highlighted the facts that seedballs are an adapted and adopted technology that is suitable for subsistence agriculture in the Sahel, but that the technology -though simple - still needs repeated demonstration. Otherwise, farmers feel unsure with respect to its application. Major errors made during application are too deep sowing at the first place, and the use of too high fertilizer additive rates or wrong fertilizer type (ammonia). 2. The agronomic evaluation of hundreds of on-farm trials shows, that seedballs are a low-risk innovation. 3. On-farm results from other projects where seedballs were tested, showed that it can be combined with OGA. OGA is an indigenous innovation where fermented urine is used for fertilization. Since seedballs only provide nutrients for the germination and establishment phase (first three weeks), OGA can support the major biomass accumulation phase. Other variants of seedballs might be successful, too.

Presentations and publications

Nwankwo, C. I., Oumarou, H. M., Nouri, M., Aminou, A. M., Herrmann, L., & Song, Y. (2022). Seed ball technology enhances pearl millet yield in a Sahelian subsistence production system. *Crop and Pasture Science*, *73*(4), 390-400. https://doi.org/10.1071/CP21158

Herrmann, L., Moussa, H.O., & Nwankwo, C.I. (March 2022). Seed Balls: Enhancing the Yield Effect in Pearl Millet and Sorghum and Disseminating the Technology in West Africa. Presentation at SMIL Administrative virtual meeting, Virtual.

Advancing improved functionality and protein quality sorghum hybrids for food applications in Ethiopia

Led by
Dr. Joseph Awika
Texas A&M University - USA

Location (department level)
Ethiopia – Sidama

Description
New sorghum hybrids under development combine high protein digestibility (HPD) mutation with waxy and heterowaxy (WX/HX) starch traits in hard endosperm show a lot of promise for various food applications due to superior functionality and improved protein nutritional quality. This project aims to advance the use of these new sorghums for food and nutrition security in Ethiopia. Based on the key findings from phase I, the research team proposes to: 1) Develop commercially viable technologies to successfully incorporate the improved sorghums in various food processes and products in Ethiopia; and 2) Establish improved HPD sorghum hybrid seed and grain production in Ethiopia. Based on phase-I findings, researchers expect that the improved sorghum hybrids can be successfully incorporated in mainstream food processing value chain to produce commercially competitive products that meet quality expectations of a broad consumer base in Ethiopia. They also expect to demonstrate that the improved sorghum hybrids will compete favorably with local hybrids in both high input and low input environments in Ethiopia. This will likely lead to a more rapid incorporation of these hybrids into local sorghum breeding and seed production systems targeting specific market applications. Addressing these objectives will lead to development of commercially viable, superior quality sorghum-based food products that will open new markets and enhance sorghum value-chain. This will benefit small-scale farmers who dominate sorghum production, and small and medium scale food enterprises (SMEs) a large portion of which are female owned. Additionally, increased utilization of HPD-sorghums in local products would significantly contribute to reduced malnutrition in children from regions that rely on sorghum as a staple.

Theory of change and impact pathways
All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet*. In addition, this project also supports *Objective II: Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet thereby extending economic benefits beyond the farmgate into the broader population.*

Collaborators
U.S. collaborating institution(s): Texas A&M University
Intl. collaborating institution(s): *Ethiopia* - Hawassa University, Ethiopian Institute of Agricultural Research (EIAR)

Achievements

The Hawassa team developed standardized protocol for making injera from sorghum and teff. These protocols have been implemented for screening the different injera formulations by sensory panels. Local sorghum, improved sorghums and novel sorghum lines were tested for a potential replacement of teff in injera making. The screening was done based on trained panelist with 24 quality descriptors for injera.

Sorghum added at <30% to teff is essentially similar in injera making quality using 100% teff. The sensory panel reported that 30% sorghum and 70% teff can make injera of similar texture and mouthfeel properties to teff injera. Among sorghum varieties, improved waxy sorghum (30%) and teff (70%) made injera of good quality (best performing of three varieties tested), followed by Merera, while the Melkam variety was least preferred because of negative characteristics like stale/musty aroma, grittiness and sour characteristics at the 30% use level. This shows that at lower percentages Melkam is needed to make injera at commercial level. Discriminative test also revealed that all the injera prepared using 30% sorghum are similar in overall sensory quality to teff injera. Panels comments on the overall quality also show that these injera are exactly like the injera on the market in Ethiopia in terms of texture and mouthfeel.

Capacity building

Individuals trained under this project include:

94	Hawassa University	Master's	Food & Science Technology
95	Hawassa University	Master's	Food & Science Technology

Lessons learned

None provided by Dr. Awika.

Presentations and publications

Awika, J.M., Rooney, W., Abegaz, K., Teferra, T.F., Mezgebe, A.G., & Tirfessa, A. (March 2022). Advancing Improved Functionality and Protein Quality Sorghum Hybrids for Food Applications in Ethiopia. Presentation at SMIL Administrative virtual meeting, Virtual.

Expanding markets for sorghum and millet farmers in West Africa through strengthening of women and youth processors and nutrition-based promotion of products

Led by
Dr. Bruce Hamaker
Purdue University – USA

Location (department level)
Niger - Niamey, Tera, Tchirozerine, Magaria
Senegal – Dakar - Burkina Faso - Kaya

Description
In phase-II, the focus of this project will be on resilience of the Hub Food Innovation Centers as convergence points for product innovation and drivers of economic and nutritional impacts for Niger and Senegal. Hub Food Innovation Centers will be strengthened to better engage with entrepreneurs, improve their effectiveness as product development centers, and bolster their sustainability. Process and product innovation of millet and sorghum foods will be enhanced by expansion of "next level" product development tools including sensory science capacity, packaging, and shelf-life assessment. These tools will enhance their support for entrepreneurs and solidify INRAN and ITA as regional R&D centers. Activities will strengthen sensory science capacity at ITA Senegal to "raise the bar" of their product development capacity and establishing their potential as a regional center of development, will complete and optimize food processes and products begun in phase-I in Niamey and Dakar to include: 1) varietal optimization in traditional and new product concepts, 2) expanded product/process optimization to include packaging and shelf-life assessment, 3) training of candidate youth from local universities, 4) facilitate youth and existing women entrepreneur processors by allowing them to use the Hub processing facilities on a fee-basis, and market products. A study will be conducted to test the hypothesis that nutritional status improvement can be achieved in rural communities in Niger through introduction of low-cost fortified millet-based foods designed with local ingredients and aligned with documented preferences of local consumers. The Hub-and-Spoke Food Innovation System will test formulations developed from phase-I activities as well as develop new high quality, safe, and nutrient-enhanced millet products using local nutrient-dense plant ingredients for food-to-food fortification and show if these locally produced products will gain a market and additionally be preferred to imported food-aid blends facilitating improved adoption by rural children in Niger.

Theory of change and impact pathways
All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet*. In addition, this project also supports *Objective II: Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet thereby extending economic benefits beyond the farmgate into the broader population* and *Objective III: Create an economically rationalized business and research investment plan to leverage USAID core financing and attract associate awards and broader donor support.*

Collaborators

U.S. collaborating institution(s):	Purdue University
Intl. collaborating institution(s):	*Senegal* - ISRA, CNRA, ITA
	Niger – INRAN

Achievements

In Niger, five rural food processing centers (i.e. Spoke Food Innovation Centers) had the highest sales and profits (USD) for fortified flour products with ~$9,000 in profit on nearly $19,000 sales since 2020 (labor is not charged by the rural women's associations in the calculation). There was the first clear indication with sales data that rural Spoke Food Innovation Centers are spreading from "secondary" spokes to "tertiary" spokes, showing an organic spread of technologies and ability of rural women processors (i.e. associations) to have successful processing enterprises. For the first time combined sales at secondary and tertiary spokes was greater than that of primary spokes. This is suggestive of sustainability aspect of rural processing and of the entry of nutritious foods into local markets, with basic support from a government-supported Hub Food Innovation Center.

In a new study, naturally fortified flour blends using improved sorghum varieties were better accepted in consumer tests in Niamey and rural Niger than the control fortified sorghum porridge made at local government community health centers. This suggests that fortified sorghum flour blends prepared to local tastes could be used more in local nutrition feeding programs. A nutrition impact study has been redesigned for rural communities in Niger with experiences gained from our FPIL Senegalese diet market assessment study. The two-part study looks at potential changes in diet quality (with nutrition status implications) at rural spoke processing sites where nutrient-fortified flour blend products were introduced over the last years. Each survey study will take 3-4 weeks. In Dakar, the sensory testing center at ITA is finished and its inauguration is set for October 20, 2022. Incubation of youth entrepreneurs is growing in both Niger and Senegal incubators (INRAN and ITA).

Capacity building

Individuals trained under this project include:

51	Purdue University	Ph.D.	Food Science
58	Cheikh Anta Diop University	Ph.D.	Microbiology
75	University of Tillabéri	Master's	Nutrition
76	Cheikh Anta Diop University	Ph.D.	Food Science & Technology
77	Cheikh Anta Diop University	Ph.D.	Food Science & Technology
79	Cheikh Anta Diop University	Master's	Plant & Microbial Biotechnology
91	University of Niamey, Niger	Master's	Food Technology
92	University of Niamey, Niger	Master's	Food Science & Nutrition
93	Cheikh Anta Diop University	Master's	Food Science

Lessons learned

The potential for rural processing of nutritious fortified foods is greater than we thought in the original design of the Hub-and-Spoke Food Processing System, with rural women actively training women of peripheral communities in food and nutrition processing technologies. This organic spread of the training of processing technologies from primary to secondary, and now to tertiary processing sites holds promise to increase consumption of more nutrient-fortified foods by children in rural areas.

Presentations and publications

Torres Aguilar, P. C. (2022). EXPERIMENTAL AND CLINICAL INVESTIGATIONS OF SLOWLY DIGESTIBLE CARBOHYDRATES FOR IMPROVED PHYSIOLOGICAL OUTCOMES AND METABOLIC HEALTH (Doctoral dissertation, Purdue University Graduate School).

Hamaker, B., Ferruzzi, M., Moussa, M., & N'Diaye, C. (March 2022). Expanding Markets for Sorghum and Millet Farmers in West Africa through Strengthening of Women and Youth Processors and Nutrition-based Promotion of Products. Presentation at SMIL Administrative virtual meeting, Virtual.

Moussa, M., Ponrajan, A., Campanella, O.H., Okos, M.R., Martinez, M.M., & Hamaker, B.R. (2022). Novel Pearl Millet Couscous Process for West African Markets Using a Low-cost Single-screw Extruder. International Journal of Food Science & Technology. https://doi.org/10.1111/ijfs.15797

Hayes, A.M., Gozzi, F., Diatta, A., Gorissen, T., Swackhamer, C., Bellmann, S., & Hamaker, B.R. (2021). Some pearl millet-based foods promote satiety or reduce glycaemic response in a crossover trial. British Journal of Nutrition, 126(8), 1168-1178. https://doi.org/10.1017/S0007114520005036

Genetic Enhancement of Pearl Millet for Yield, Biotic and Abiotic Stress Tolerance in West Africa (GENMIL)

Led by

Dr. Ndjido Kane
Institut Sénégalais de Recherches Agricoles (ISRA)/CERAAS – Senegal

Location (department level)

Niger – Niamey
Senegal – Thies, Bambey

Description

Drought, diseases, and insects are key constraints for millet production in West Africa. There is a recognized need for rapid advancement in the development of varieties addressing these constraints and taking into consideration farmer's practices and market acceptability. This project aims to accelerate the development of a combination of pearl millet (PM) innovations to put into farmers hands that at finite will result in sustainable productivity enhancement of PM for food security and income generation. Specific objectives are: i) modernizing INRAN and ISRA breeding program to deliver high-yielding PM cultivars that tolerate drought, *Striga* and downy mildew in Niger and Senegal; ii) assisting production with adapted and resilient farmer's practices and crop management strategies; iii) co-developing and up-scaling selected options of integrated genetic, natural resource management context to improve PM production; and iv) empowering human and institutional capacities.

The five-year research project (2019-2023) is compartmentalized to meet these 4 specific objectives, relying on series of activities and strategic criteria. A first criterion is dialogue between scientists and farmers and back-and-forth with end-users for a high rate of adoption of PM innovations. The activities around will consist of promoting adoption and advocating the uses and benefits of new PM technologies, within an innovative platform gathering actors of the value chain (stakeholders, private sector, farmer's organizations, extension services, scientists). Sharing material and knowledge will bring on germplasm originating from West Africa, from Niger and Senegal. Genetic materials either available or being developed will be shared between teams and research programs. Breeding Management System (BMS) will be used as standardize unique management and sharing resources (plant materials and data) system. Germplasm will be evaluated in both Senegal and Niger. Inter population improvement approach of reciprocal recurrent selection (RRS) method will be applied using selected populations to make use of both general and specific combining ability. Recent phenotyping and genotyping approaches will be conducted to evaluate the germplasm and identify/validate major quantitative traits loci (QTLs) for tolerance to drought, resistance to major biotic stresses in Senegal and Niger (complementary and co-working). Farming practices coping with diseases or ecologically intensifying production will be added into the breeding product profile (co-conceptualization). All identified elite cultivars will be integrated into local breeding programs (co-breeding) and evaluated on-farm for performance and farmer/market acceptability (scaling-up). Mentoring of early career research and continuous empowering of young trainees (Ph.D. an MSc), farmers and seed producers will contribute to human and institutional capacity building needed to modernize sustainable PM breeding programs across the NARIs.

Theory of change and impact pathways

All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet.* In addition this project also supports *Objective II: Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet thereby extending economic benefits beyond the farmgate into the broader population.*

Collaborators

U.S. collaborating institution(s): Kansas State University

Intl. collaborating institution(s): *Senegal* - Institut Sénégalais de Recherches Agricoles (ISRA), Centre d'Etudes Régional pour l'Amélioration de l'Adaptation à la Sécheresse (CERAAS)
Niger - International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Institut National de la Recherche Agronomique du Niger (INRAN)

Achievements

Considerable outreach and dissemination of new varieties was combined with continued development of new pearl millet varieties and hybrids in Senegal and Niger. In Senegal, one and half tons of new varieties were distributed among 900 lead farmers, potentially reaching 7900 end-users in 2023. Fifty farmers were trained on seed production and multiplication in our community-based seed multiplication activities. We registered a high demand of hybrid seed of ICMH 17711 from all actors and sectors of the value chain. It was supplied to ISRA-Senegal and INRAN-Maradi, Niger. Yield testing trials were established in collaboration with ISRA in Senegal and INRAN-Maradi in Niger in Sahelian and Sudanian zone for varieties and hybrid. Amate seed company and Alheri seed company have produced the hybrid seeds on 1 ha each for ICMH 177111, SONU and ICMH 187333 during the offseason of 2021 and Amate has reached 300 farmers in the rainy season 2022.

The breeding program is developing new lines for the three product concepts identified using trait discovery, high throughput phenotyping and deep learning, anatomics and SNPs markers. Development of BCNAM from BC1F2 to BC1F3 is ongoing in this rainy season of 2022 making progress in A4 fertility restoration marker validation. F2 seeds have been sent to ISRA- Senegal for further phenotyping for fertility and sterility and analyzing of the marker for A4 restoration. Seeds for phenotyping of PMIGAP-WCA lines in Senegal were distributed to ensure a regular supply of new varieties in the future.

Capacity building

Individuals trained under this project include:

72	Colorado State University	Ph.D.	Plant breeding and genetics
88	Ecole Nationale Supérieure d'Agriculture	Engineer	Agricultural Engineering

Lessons learned

The variety SOUNA 3 widely used and adopted is not responding to the need of the stakeholders - yield is very low without high inputs added making it very difficult to get an acceptable production for subsistence farmers.

Presentations and publications

Kane, N., Gislain, K., Issoufou, K.A., & Prakash, G. (March 2022). GENMIL: Genetic Enhancement of Pearl Millet for Yield, Biotic and Abiotic Stress Tolerance in Niger and Senegal. Presentation at SMIL Administrative virtual meeting, Virtual.

Enabling Marker Assisted Selection for Sorghum Disease Resistance in Senegal and Niger

Led by
Dr. Clint Magill
Texas A&M University - USA

Location (department level)
Niger – Niamey
Senegal – Thies, Bambey

Description
Research collaboration between Texas A&M, INRAN, and ISRA extended to include researchers at nearby Universities in Niger and Senegal will result in the identification or creation of disease-resistant, locally adapted, sorghum cultivars that maintain properties preferred by farmers and consumers alike. Target diseases are anthracnose and long smut in Niger and anthracnose and grain mold in Senegal. The cultivar creation aspect will be derived from the ability to track resistance genes or quantitative trait loci (QTLs) with DNA-based tags that can be economically scored, in-country, through the development of allele-specific PCR primers at TAMU. Marker tagging will use Genome Wide Association studies to identify Single Nucleotide Polymorphisms (SNPs) derived from sources of genetic resistance identified in each country. F2 or later generation DNA samples from resistant and susceptible progeny of segregating crosses will identify markers associated with disease response. This technology will enable breeders to take advantage of marker assisted selection to greatly speed the development of cultivars with resistance to new races of the pathogens that are certain to occur over time. Publications in scientific journals will inform other scientists interested in sorghum pathology and genomics while demonstrations and interactions with local farmers unions, including sorghum growers, will showcase the value of growing disease-resistant cultivars.

Theory of change and impact pathways
All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet*. In addition this project also supports *Objective II: Incubate and nurture a new wave of feed and food products to stimulate demand for sorghum and millet thereby extending economic benefits beyond the farmgate into the broader population*.

Collaborators

U.S. collaborating institution(s):	Texas A&M University, USDA-ARS
Intl. collaborating institution(s):	*Senegal* - Institut Sénégalais de Recherches Agricoles (ISRA), Centre d'Etudes Régional pour l'Amélioration de l'Adaptation à la Sécheresse (CERAAS) *Niger* - Institut National de la Recherche Agronomique du Niger (INRAN), University of Tillabéri

Achievements
Dr. Mame Penda Saar arranged for a documentary related to the Senegalese disease survey to be made by professionals. It has been available for viewing nationally on television. The documentary has been widely shown in Senegal. Coumba Fall spent a month in Senegal to collect dried leaf samples of a segregating population and has extracted DNA from over 100 samples. At this time we do not have disease data for the progeny, so GWAS analysis has yet to be conducted. Three manuscripts were published recognizing SMIL as a source of funding. Dhurrin levels in seedings of 60 Senegal and 60 Niger cultivars were measured. Leaf samples from 2 segregating F4 populations (anthracnose) developed in Senegal have been successfully used for DNA extraction in Texas. The response of Senegalese cultivars available in the US germplasm collection were surveyed for response to anthracnose and single nucleotide polymorphism associated with disease response were identified.

Capacity building

Individuals trained under this project include:

69	University of Tillabéri	Master's	Plant Pathology/Plant Breeding
86	Texas A&M University	Ph.D.	Plant Pathology and Microbiology
96	Esimad Academy in Niger	Bachelor's	Agricultural Engineering
97	Texas A&M University	Master's	Agricultural Engineering

Lessons learned

When meeting in person is not possible, Zoom conferences provide an alternative. However, lack of bandwidth creates a significant problem for our colleagues in Africa. Bringing unidentified fungal samples to the US was futile, as they were confiscated by customs at the DFW airport, even though they were non-viable (fixed in alcohol) which means they are not subject to quarantine. Attempts to extract DNA without the use of liquid nitrogen gave very low levels of product and it was not of sufficient quality for use in sequencing. This seems to eliminate the possibility of getting useful DNA directly from Niger or Senegal.

Presentations and publications

Ahn, E., Fall, C., Prom, L. K., & Magill, C. (2022). Genome-wide association study of Senegalese sorghum seedlings responding to a Texas isolate of Colletotrichum sublineola. *Scientific Reports*, *12*(1), 1-7. https://doi.org/10.1038/s41598-022-16844-6

Ahn, E., Fall, C., Fan, F., Prom, L. K., & Magill, C. (2022). Johnsongrass rhizome tissue can be infected by Colletotrichum sublineola. *Physiological and Molecular Plant Pathology*, *121*, 101860. https://doi.org/10.1016/j.pmpp.2022.101860

Ahn, E., Prom, L. K., Fall, C., & Magill, C. (2022). Response of Senegalese Sorghum Seedlings to Pathotype 5 of Sporisorium reilianum. *Crops*, *2*(2), 142-153. https://doi.org/10.3390/crops2020011

Magill, C., Fall, C., Haougui, A., Mame, S.P., & Prom, L.K. (March 2022). Enabling Marker Assisted Selection for Sorghum Disease Resistance in Senegal and Niger. Presentation at SMIL Administrative virtual meeting, Virtual.

Durable adaptation to aphid and drought for smallholder sorghum in the Americas

Led by

Led by Dr. Geoffrey Morris – Colorado State University, Dr. Gael Pressoir – CHIBAS, Université Quisqueya

Location (Department Level)

Haiti

Description

Globally, there is great interest in applying new genomic technologies to accelerate genetic gains in developing country breeding programs. However, these methods have not been adopted in developing country level National Agricultural Research Institutes (NARI) due a mismatch between available genomic selection approaches and the existing operations of NARI breeding programs. This project aims to develop genomic approaches from within a NARI breeding program to reduce barriers for adoption. Specifically, these improved genomics selection approaches will be deployed to address several key constraints for dual-purpose sorghums used by smallholders in Haiti. The targets will be improving grain yield while maintaining forage yield and quality, improving tolerance to low/high pH soils, and improving tolerance to post-emergence and post-flowering water limitation.

By designing genomics-assisted breeding approaches in a NARI, the resulting technology will be better suited for adoption by other NARI globally. The tools and resources developed in this project will facilitate adoption of genomics-assisted breeding by partner programs in West and East Africa and will be diffused globally via breeding informatics initiatives (GOBII and BMS).

Launch of Haiti project: "Durable adaptation to aphid and drought for smallholder sorghum in the Americas"

When the associate award ended in 2021, the ME developed a follow-on project to ensure continuity. This project, "Durable adaptation to aphid and drought for smallholder sorghum in the Americas" will extend the work started under the associate award. This project will ensure that innovations on aphid and drought resilient varieties by the Université Quisqueya (UniQ) sorghum program led to durable solutions for smallholder farmers and downstream stakeholders in Haiti. Further, we will develop technology to facilitate the diffusion of the technology from Haiti to other smallholder-serving breeding programs in Latin America and beyond. The project launched in the second quarter of 2021 and has been progressing on schedule. The US-based members of the project team have been recruited and onboarded, the project team in the US and Haiti have been meeting regularly. The Haiti team has conducted their field activities on schedule despite the political unrest and security problems in Port-au-Prince, the earthquake in the south (near the breeding station in Cayes), and the move of the program from Port-au-Prince to Mirebalais.

Theory of change and impact pathways

All research projects contribute towards *Objective I* of our theory of change, *Build a coalition of science and industry around sorghum and millet*. In addition this project also supports *Objective III: Create an economically rationalized business and research investment plan to leverage USAID core financing and attract associate awards and broader donor support.*

Collaborators

U.S. collaborating institution(s): Colorado State University, Cornell University

Intl. collaborating institution(s): *Haiti* – CHIBAS, Université Quisqueya

Achievements

The Haiti project builds upon the success of the associate award and continues to focus on building stronger relationships between applied sorghum breeding, biology and genetics while increasing the human and institutional capacity in Haiti. Achievements this year include the continued rapid generation of new crosses combined with phenomic and genomic analysis to produce a "Flywheel Genomics" platform where information, coming from all sides, accelerates and sustains sorghum varietal improvement. Results from this process confirm that there is a second locus of sugarcane aphid resistance and a third, yet minor, source. Differences in resistance were noted in comparison between materials with RMSE1 alone and RMSE1 combined with the two new loci.

Success with building durable sugarcane aphid resistance has allowed the program to realign resources on creating differentiated market classes targeting farmers in marginal environments who consume grain locally and value-added traits for industrial usages in food, beverage and feed. At the same time, these new product targets can be built with durable sugarcane aphid resistance. A deep analysis of the resistance found that it is related to foliar cyanide content and with this knowledge can help manage products and their target niche. For example, these materials would not be targeted at forage uses.

Capacity building

Individuals trained under this project include:

67	Cornell University	Ph.D.	Plant breeding and genetics

An additional aim of the project was to train the next generation of US researchers for careers in smallholder-serving R&D. A MSc student (female; Kristen Johnson; 05/21–) and a postdoc (male; Brian Rice; 10/21–) have been recruited onto the project, and an additional Ph.D. student (male; Carl VanGessel; 07/21–) funded by a Colorado State University fellowship, is also participating on the project. Kristen is testing hypotheses on the role of the cyanogenic glycoside dhurrin in UniQ's drought tolerance and stay-green traits, which will provide critical information to guide the UniQ breeding program (and others) on potential tradeoffs for forage quality and drought tolerance. Brian is developing and implementing new genomic methods that will accelerate UniQ's genetic gain for complex interrelated traits (aphid resistance, drought tolerance, forage quality, grain, and forage yield) and facilitate the transfer of useful traits to other smallholder-serving programs. Carl is working to understand the genetic and physiological basis of the *RMES1* aphid resistance used by UniQ, to head-off any tradeoffs or vulnerabilities in this defense mechanism and facilitate the discovery of new resistance mechanisms. We're also working closely with early-career faculty member Terry Felderhoff (Kansas State University), leveraging funding from Innovative Seed Systems (e.g., Dekalb sorghum brand), to develop new aphid-resistance marker technology that will combat the aphid across the Americas.

Lessons learned

The multi-institutional and disciplinary composition of the project has built a highly interactive flywheel of activity that requires high levels of dedication among all participants. The "Flywheel Genomics" platform takes in energy from all participants and returns energy in the form of additive knowledge that accelerates the varietal development process and allows for greater differentiation of market classes.

Presentations and publications

Muleta, K., Felderhoff, T., Winans, N., Walstead, R., Charles, J.R., Armstrong, J.S., Mamidi, S., Plott, C., Vogel J.P., Lemaux, P.G., Mockler, T.C., Grimwood, J., Schmutz, J., Pressoir, G., & Morris, G.P. (2022). The recent evolutionary rescue of a staple crop depended on over half a century of global germplasm exchange. Science advances, 8(6), eabj4633. https://doi.org/10.1126/sciadv.abj4633

Morris, G.P., Charles, J.R., Cheremond, Y., Johnson, K., Pressoir, G., Rice. B., & VanGessel, C. (March 2022). Durable Adaptation to Aphid and Drought for Smallholder Sorghum in the Americas. Presentation at SMIL Annual Conference, Virtual.

Human and Institutional Capacity Development

Local and institutional capacity development is a core outcome of the Sorghum and Millet Innovation Lab's global research for development network. The program developed a network of global talent, resources, and capacity to address country-specific technology and development issues. Most of the 97 SMIL/USAID sponsored long-term training students have completed their degrees and are back in their countries contributing to the research community as they engage in their respective national research programs. The SMIL ME, along with our community of university research teams, are supporting returning these young career scientists. As an example, Dr. Ousmane Seyni and Dr. Moustapha Moussa (Niger) are Principal Investigators and Co-PIs on several USAID funded proposals to further develop sorghum forage and seed systems, which was facilitated by the SMIL ME. Three long-term Ph.D. female graduate students continue their programs of study in US universities. Short-term trainings have strongly continued despite the challenges of political and security risks in West Africa and Ethiopia.

Short-term training

In FY22, SMIL facilitated the short-term training of 1,586 individuals across 16 different training events. The types of short-term trainings conducted varied, and included farmer trainings, professional workshops, on-the-job capacity-building exercises, and academic courses.

Of the 1,586 trainees, producers made up the largest group with 1,332 people trained, followed by 144 people in private sector firms, 81 civil society members (predominantly researchers and students), and 29 people in government. Of the total trainees, 654 were female and 932 were male.

Table 1 Short-term trainees supported by the Sorghum and Millet Innovation Lab – FY 2022 (Phase-II)

Country of Training	Purpose of Training	Who was trained	Number trained		
			M	F	Total
Niger	Seed Registration Workshop with Niger National MoA Committee	Producers	8	5	13
Niger	Annual workshop and training for producers	Producers, Private Sector	36	4	40
Niger	Monitoring tour	Producers	45	5	50
Senegal	Training of seed producers in hybrid and OPVs pearl millet seed production	Producers, Government, Private Sector	45	5	50
Ethiopia	Strategies for development of commercial food sorghum processing sector in Ethiopia	Producers, Government, Private Sector, Civil Society	16	6	22
Madagascar	Training south Madagascar farmers to sorghum seed production and adoption of suitable agronomic practice to enhance sorghum production	Producers, Private Sector, Civil Society	54	12	66
Niger	Training on Striga germination assay in pots and planting sorghum genotypes for outsourcing genotyping assay	Civil Society	2	4	6

Country of Training	Purpose of Training	Who was trained	Number trained		
			M	F	Total
Niger	Seed ball caravan in Maradi	Producers	590	474	1064
Niger	Training on FRN-App (data clinic)	Producers, Private Sector	45	5	50
Niger	Training and backstopping of youth entrepreneurs in millet and sorghum grain processing at the INRAN Food Innovation Hub in Niamey	Producers, Government, Private Sector, Civil Society	8	20	28
Niger	Management, Marketing and Backstopping and Support in Business Development for Young and Women Entrepreneurs and related actors operating in Millet and Sorghum Grain Processing in Niamey	Private Sector, Civil Society	6	15	21
Niger	Workshop on implementation of the Nutritional Assessment of Impact of the Nutrient Fortified Millet Flour	Private Sector, Civil Society	10	20	30
Senegal	Training in processing high quality couscous products	Producers, Government, Private Sector	14	36	50
Senegal	Food product formulation development for targeting recommended daily allowances of key macro- and micronutrients in infant foods	Private, Sector, Civil Society	23	27	50
Senegal	Knowledge and Capacity Building Workshop on Gender and Nutrition Sensitive Technologies and Innovations (T&I) in Agribusiness Development	Producers, Private Sector, Civil Society	14	16	30
Ethiopia	Genome-wide association analysis, genetic male sterility system in sorghum and parental line development for hybrid program	Government	16	0	16

Long-term training

In FY22, the Sorghum and Millet Innovation Lab saw the graduation for three long-term trainees while seven long-term trainees started their training, bringing the total to 97 long-term trainees during phase-I and phase-II combined.

Among those 97 trainees, 66 are male and 31 are female. The group also represents a variety of degree levels with 3 agricultural engineers, 7 Bachelor's degrees, 44 Master's degrees, 39 doctoral degrees (Ph.D.) and 4 post-doctoral studies.

Table 2 Long-term trainees supported by the Sorghum and Millet Innovation Lab – FY 2022 (Phase-I & Phase-II)

Trainee Number	Sex	University	Degree	Major	Graduation date	Degree granted?	Home Country
1	Male	Universite Prive de Segou Agri SUP	Bachelor's	Agronomy	Dec-18	Yes	Mali
2	Male	INRAN	Bachelor's	Agronomy	Nov-17	Yes	Niger
3	Female	CERAAS	Bachelor's	Agronomy	Jan-17	Yes	Niger
4	Male	ICRISAT – Niger	Bachelor's	Ecophysiology	Dec-18	Yes	Niger
5	Female	CERAAS	Bachelor's	Agronomy	Jan-17	Yes – Pursuing Master's degree at University Cheikh Anta Diop	Senegal
6	Male	ISFAR/University of Thies	Agricultural Engineer	Agricultural Engineering	Jul-17	Yes – on an internship with an agricultural enterprise	Senegal
7	Female	ISFAR/University of Thies	Engineer	Agricultural Engineering	Jul-16	Yes – has been recruited by agricultural firm, SODAGRI	Senegal
8	Male	University of Ouagadougou	Master's	Breeding and conservation of seed	Apr-17	Yes	Burkina Faso
9	Female	INERA	Master's	Seed selection and conservation (SELCOSE)	Dec-15	Yes	Burkina Faso
10	Male	Hawassa University	Master's	Food science and postharvest technology	Dec-18	Yes	Ethiopia
11	Female	Haramaya University	Master's	Plant pathology/ breeding	May-18	Yes	Ethiopia
12	Male	Haramaya University	Ph.D.	Plant pathology/ breeding	Oct-17	Yes - now pursuing Ph.D. at Haramaya University	Ethiopia

Trainee Number	Sex	University	Degree	Major	Graduation date	Degree granted?	Home Country
13	Male	Kansas State University	Master's	Agricultural Economics	May-18	Yes - now pursuing Ph.D. at Kansas State University	Ethiopia
14	Male	CHIBAS	Master's	Genetics	Nov-17	Yes	Haiti
15	Male	INRAN	Master's	Socio-economy	Jan-18	Yes	Niger
16	Male	Université Abdou Moumouni de Niamey	Master's	Entomology	Jan-18	Yes	Niger
17	Male	Universite Dan Dicko Dankoulodo	Master's	Agronomy	Dec-17	Yes	Niger
18	Male	Université Abdou Moumouni de Niamey	Master's	Entomology	Jan-18	Yes	Niger
19	Male	University of Tahoua	Master's	Socio-economy	Dec-17	Yes	Niger
20	Male	Ecole National Superieure d'Agriculture (ENSA)	Master's	Production Végétales	Jan-16	Yes	Senegal
21	Male	ENSA Thies	Master's	Socio-economy	Dec-17	Yes	Senegal
22	Female	ITA	Master's	Agricultural Economics	May-16	Yes	Senegal
23	Male	CERAAS	Master's	Microbial and vegetal biotechnology	Sep-17	Yes	Senegal
24	Male	University Cheikh Anta Diop	Master's	Pest Management	May-17	Yes	Senegal
25	Female	ENSA/University of Thies	Master's	Sustainable development and society/agriculture	Aug-17	Yes	Senegal
26	Male	University of Thies	Master's	Agricultural engineering	Apr-17	Yes	Senegal
27	Male	Universite de Thies	Master's	Agricultural Economics	Apr-17	Yes	Senegal
28	Male	CERAAS	Master's	Breeding	Apr-16	Yes	Côte d'Ivoire
29	Male	Haramaya University	Master's	Plant pathology/breeding	Dec-15	Yes – works for BAKO Research	Ethiopia

Trainee Number	Sex	University	Degree	Major	Graduation date	Degree granted?	Home Country
						Center at Oromia Research Institute	
30	Female	Hawassa University	Master's	Food Processing and Preservation	Mar-17	Yes – employed at a private company	Ethiopia
31	Male	Haramaya University	Master's	Agronomy	Jul-16	Yes - working for Oromia Agricultural Research Institute, Fedis Research Center	Ethiopia
32	Female	Abdou Moumouni University of Niamey with Short Training at Virginia Tech	Master's	Agricultural Economics	Jan-18	Yes	Niger
33	Female	University Cheikh Anta Diop	Master's	Pest management	Dec-15	Yes	Senegal
34	Male	ISRA	Master's	Agroforestry ecology and adaptation	Nov-18	Yes	Senegal
35	Female	ISRA	Master's	Analytical Chemistry	Jul-18	Yes	Senegal
36	Male	Virginia Tech	Master's	Agricultural Economics	May-16	Yes – works for U.S. Peace Corps in the Philippines	United States
37	Male	Kansas State University	Ph.D.	Agricultural Economics	Jul-18	Yes - working at the FAO	Burkina Faso
38	Male	Purdue University	Ph.D.	Plant breeding and genetics	May-19	Yes - now pursuing Ph.D. at Purdue University	China
39	Male	Purdue University	Ph.D.	Plant pathology	Dec-20	Yes	Ethiopia
40	Male	Kansas State University	Ph.D.	Plant breeding and genetics	Dec-19	Yes	Ethiopia
41	Male	Kansas State University	Ph.D.	Plant pathology/breeding	Dec-20	Yes	Ethiopia
42	Female	Purdue University	Ph.D.	Food science	Aug-18	Yes - working as a post-doc at North Carolina State University	Ethiopia

Trainee Number	Sex	University	Degree	Major	Graduation date	Degree granted?	Home Country
43	Male	University of Pretoria	Ph.D.	Food Science	Jul-18	Yes - working at Hawassa University	Ethiopia
44	Male	Purdue University	Post-doctoral studies	Plant breeding and pathology	May-21	Yes	Ethiopia
45	Male	Texas A&M	Ph.D.	Food Science	Dec-18	Yes - working at Hawassa University	Ethiopia
46	Female	Purdue University	Ph.D.	Agronomy	Dec-18	Yes	Germany
47	Male	University of Maradi	Ph.D.	Entomology	Dec-19	Yes	Niger
48	Male	West Texas A&M University	Ph.D.	Plant, Soil and Environmental Science - Insect Pest Management	May-19	Yes - working at INRAN	Niger
49	Male	ICRISAT – Niger	Ph.D.	Entomology	Dec-19	Yes	Niger
50	Female	Kansas State University	Ph.D.	Agronomy (Plant Breeding & Genetics)	May-20	Yes	Niger
51	Male	Purdue University	Ph.D.	Food Science	Dec-19	Yes - working at INRAN	Niger
52	Male	West African Center for Crop Improvement	Ph.D.	Plant Breeding	May-19	Yes - working at INRAN	Niger
53	Female	University of Hohenheim	Master's	Agronomy/Soil science	Feb-19	Yes	Niger
54	Male	University of Hohenheim	Post-doctoral studies	Agriculture	Sep-18	Yes	Nigeria
55	Male	Kansas State University	Ph.D.	Plant breeding and genetics	Dec-17	Yes - crop genetics post-doc at the University of Illinois	Nigeria
56	Male	CERAAS	Ph.D.	Plant breeding and genetics	Dec-19	Yes - working at CERAAS	Senegal
57	Female	West African Center for Crop	Ph.D.	Plant Breeding	Jul-19	Yes - working for ISRA/CERAAS on Sorghum Trait Development Pipeline	Senegal

Trainee Number	Sex	University	Degree	Major	Graduation date	Degree granted?	Home Country
		Improvement					
58	Male	Cheikh Anta Diop University/ITA	Ph.D.	Microbiology	Sep-23	No	Senegal
59	Female	Cheikh Anta Diop University	Ph.D.	Food Science and Nutrition	Jul-18	Yes	Senegal
60	Male	Kansas State University	Ph.D.	Agronomy (Plant Breeding & Genetics)	May-20	Yes	Senegal
61	Female	University Cheikh Anta Diop	Ph.D.	Entomology	Dec-17	Yes	Senegal
62	Female	University of Thies	Ph.D.	Pest management	Dec-17	Yes	Senegal
63	Female	University Cheikh Anta Diop	Ph.D.	Pest management	Dec-17	Yes	Senegal
64	Male	CERAAS	Ph.D.	Agronomy (Breeding & Genetics)	Jan-18	Yes - working at ITRA in Togo	Togo
65	Male	Purdue University	Ph.D.	Plant Genetics	May-16	Yes – works at Makerere University in Uganda	Uganda
66	Female	Purdue University	Ph.D.	Food Science and Nutrition	Aug-19	Yes	USA
67	Female	Cornell University	Ph.D.	Plant breeding and genetics	Aug-21	Yes	USA
68	Male	Purdue University	Post-doctoral studies	Plant Genetics	Jun-17	Yes	Nigeria
69	Male	University of Tillabéri	Master's	Plant Pathology/Plant Breeding	May-21	Yes - working at INRAN	Niger
70	Male	Universite Abdou Moumouni Niamey	Ph.D.	Crop Physiology	May-23	Yes –pursuing Ph.D. at Universite Abdou Moumouni Niamey	Niger
71	Male	Universite Abdou Moumouni Niamey	Ph.D.	Crop Physiology	May-23	Yes - pursuing Ph.D. at Universite Abdou Moumouni Niamey	Niger

Trainee Number	Sex	University	Degree	Major	Graduation date	Degree granted?	Home Country
72	Female	Colorado State University	Ph.D.	Plant Breeding and genetics	Jun-23	No	Senegal
73	Female	University Cheikh Anta Diop	Master's	Plant and microbial biotechnology	Oct-20	Yes	Senegal
74	Male	University of Hohenheim	Master's	Agritropics	Jul-20	Yes	United States
75	Male	University of Tillabéri	Master's	Food Science and Nutrition	Dec-22	No	Niger
76	Male	Cheikh Anta Diop University	Ph.D.	Food Science and Technology	Dec-22	No	Senegal
77	Male	Cheikh Anta Diop University	Ph.D.	Food Science and Technology	May-23	No	Senegal
78	Male	Cheikh Anta Diop University	Ph.D.	Food Science and Nutrition	May-23	No	Senegal
79	Male	Cheikh Anta Diop University	Master's	Plant and microbial biotechnology	Oct-20	Yes	Senegal
80	Male	Ambo University, EIAR, Assosa Research center	Ph.D.	Plant Pathology	Sep-22	No	Ethiopia
81	Male	University of Hohenheim	Master's	Agricultural Engineering	Aug-20	Yes	Germany
82	Female	University of Niamey	Master's	Food Science and Nutrition	Dec-22	No	Niger
83	Male	Haramaya University	Master's	Plant Breeding	Jul-22	No	Ethiopia
84	Male	Mekelle University	Ph.D.	Plant Breeding	Jul-23	No	Ethiopia
85	Female	Kansas State University	Ph.D.	Agricultural Economics	Jul-25	No	Ethiopia
86	Female	Texas A&M University	Ph.D.	Plant Pathology and Microbiology	Jul-23	No	Senegal
87	Male	University of Hohenheim	Post-doctoral Studies	Rural Sociology	Dec-22	No	Ghana

Trainee Number	Sex	University	Degree	Major	Graduation date	Degree granted?	Home Country
88	Male	Ecole Nationale Supérieure d'Agriculture	Engineer	Agricultural Engineering	Jul-21	No	Senegal
89	Male	Ethiopia Institute of Agricultural Research (EIAR)	Master's	Plant Breeding	Jul-22	No	Ethiopia
90	Female	National Institute of Agricultural Research of Niger (INRAN)	Bachelor's	Agriculture	May-24	No	Niger
91	Male	University of Niamey, Niger	Master's	Food Technology	Jul-23	No	Niger
92	Female	University of Niamey, Niger	Master's	Food Science & Nutrition	Jun-23	No	Niger
93	Female	Cheikh Anta Diop University	Master's	Food Science	Jun-23	No	Senegal
94	Male	Hawassa University	Master's	Food Science and Technology	Mar-23	No	Ethiopia
95	Male	Hawassa University	Master's	Food Science and Technology	Sep-22	No	Ethiopia
96	Female	Esimad Academy in Niamey, Niger	Bachelor's	Agricultural Engineering	May-22	No	Niger
97	Male	University of Tillabéri	Master's	Agricultural Engineering	Mar-23	No	Niger

Institutional development

The SMIL ME has, from its inception, been fully vested in localization and nationally defined and led research for development strategies. Another example of this was the facilitation by the SMIL ME of a university partner tour by the DG of ISRA/CERAAS to multiple US universities and other innovation lab ME in the US, culminating with a joint consultation at the University of Georgia where USAID, BMGF, SMIL, ILCI, PIL, and CIMMYT were represented. Dr. Ndjido Kane, Dr. Khady Nani Dramé, and Dr. Daniel Fonceka represented ISRA/CERAAS at this meeting in which our national partner presented its long term institutional vision, scaling / commercialization strategies, national and international partner network which was documented in a meeting summary report. This meeting also provided opportunities for the IL's (of which ISRA/CERAAS works with 8 IL), BMGF, and CIMMYT to better coordinate their external support aligned and localized with the national partner strategic plan. One aspirational vision of ISRA/CERAAS is an upgraded research coordination and collaboration campus "Mbolo" (unity). A design concept, architectural

drawings, and models were developed at Kansas State University College of Architecture to further communicate this vision to decision makers and potential donors.

SMIL has also supported ISRA/CERAAS in the further development of its technology transfer unit led by Dr. Dramé. Key exchange opportunities for Dr. Dramé to other innovation labs / universities and engagement with USAID Innovation Lab Council meeting in which she presented on localization were also organized. Under her leadership, the SMIL ME will be cooperating to fund several key technology transfer initiatives in the next 10 months.

In Ethiopia, the SMIL ME also financed and technically supported the Ethiopian Miller's Association (EMA) and the Ethiopian Standards Association (ESA) to develop and initiate the registration of standards for sorghum flour and grain which had not previously existed. This institutional support will assist any milling and food product company as it considers sorghum milling and food product development and sales.

The institutional networks made up of the genomics assisted breeding platforms have continued to grow and reinforce research capacity in West Africa. This regional cooperative model allows national program scientists to specialize in the development of traits that are of the highest importance to their nation while relying upon colleagues in other countries to do the same for other traits. Being part of a network allows one nation to draw upon the scientific advances of another so that pyramiding of traits becomes less time intensive. The network approach is far more cost- and time-effective than developing expertise for every single stressor in each country of the region, as presented in Figure 3. Improved seed and parent materials within this platform are now also being considered for sharing in south Sudan, north Sudan and Madagascar where SMIL has been asked by seed system actors for access to these materials for local adaptation studies, plant breeding programs and seed commercialization.

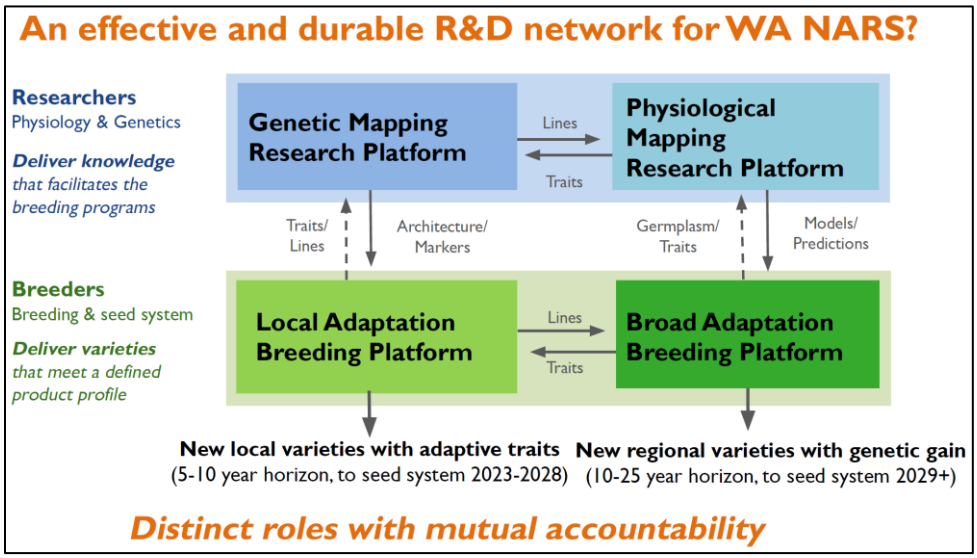


Figure 3 R&D network for WA NARS from Morris project proposal

A similar approach to the pearl millet West Africa breeding network is being developed based on the success of the decentralized sorghum breeding network. The Genetic Enhancement of Pearl Millet for Yield, Biotic and Abiotic Stress Tolerance in West Africa (GENMIL) research project, led by Dr. Ndjido Kane, is supporting this regional local institutional capacity strengthening based within the existing NARS structure/teams. Improved seed and parent materials within this platform are now also being considered for sharing in south/north Sudan where SMIL has been asked by seed system actors for access to these materials for local adaptation studies, plant breeding programs and seed commercialization.

We have also developed a similar, albeit smaller, network to test the hypothesis that Haiti, and other small countries like Haiti, can benefit from genomics-enabled breeding. Many argue that this is difficult given the capital-intensive nature of genomics, but this opinion largely rests on the "go it alone" proposition that national expertise is needed in all the elements of genomics and breeding programs. The Feed the Future Innovation Lab for Genomics-enabled Breeding, administered by the Sorghum and Millet Innovation Lab, challenged this hypothesis by breaking the process into tasks and distributing these tasks to different collaborators. In the case of Haiti, Quisquenya University and CHIBAS took responsibility for high quality phenotyping of sorghum germplasm assembled from many global sources to identify susceptible and resistant line against the sugarcane aphid. Cornell University developed the tools to capture DNA from these materials and processes for genomic analysis. Kansas State University was charged with bioinformatic analysis. This process facilitated the rapid cycling of testing and evaluation to identify the loci of the sugarcane aphid resistance genes and introgression into highly productive sorghum varieties in Haiti. Small countries can indeed benefit from genomics-enabled breeding especially when part of a cost-effective team.

The COVID-19 global environment allowed the SMIL program network to adapt. Videoconferencing, onsite virtual communications to the network and specific communications capacity strengthening have all assisted our network to strengthen its capacity to facilitate and better communicate research for development impact.

Innovation Transfer and Scaling Partnerships

Development and commercialization of sorghum and pearl millet technologies is a key driver of the SMIL program. Our investment across the value chain (breeding, production systems, value addition) as well building cooperation with multiple actors along the value chain builds demand for relevant technologies and expert technical input. In each focus country the SMIL ME has cooperated with our national partners in their own localization of innovation transfer. The further development of working partnerships across the value chain to strengthen commercialization is also evident.

The SMIL ME has been of strategic assistance to ISRA/CERAAS in their development of a technology transfer unit. Personnel and administrative costs for the technology transfer head, Dr. Nani Dramé, and unit was supported with targeted additional funding. The SMIL ME will be cooperating to fund several key technology transfer initiatives under this unit that support further commercialization of technologies, linkages to existing technology sharing platforms, and advocacy with national government for sorghum and pearl millet-based food products.

For the seed sector, commercialization of improved seed technologies is a key objective of SMIL and our national partners. Strengthening the seed system in each focus country to enable and support greater commercialization of improved seed is being addressed. A sorghum seed system meeting was convened in Ethiopia with financial support by SMIL in cooperation with our national partners to consider the current state of the public, private, and community-based seed pathways, gaps, and key steps in the next 10 months, alignment with Agricultural Commercialization Cluster, national approach, and longer-term strengthening aspects. A full report of the meeting, breakout groups, and key recommendations is being compiled by the Agricultural Transformation Institute (ATI). Public and private seed system participants also attended this meeting from Juba and Khartoum. Exchange of improved sorghum and pearl millet seed as well as parent materials is being organized.

Smallholders often access their seed through multiple channels of which the informal seed system can account for up to 90% for sorghum and pearl millet smallholder producers in west and east Africa. Additional specific funds were provided to ISRA/CERAAS and EIAR to multiply foundation seed for further scaling through community-based seed system approaches which are based on empowering smallholders and local farmer associations to maintain and multiply improved seed for their members.

The ongoing development of technical partnerships with food product companies, such as Mamelles Jaboot, in Dakar has continued. The SMIL ME also entered into a formal technical cooperation with the DINA Food Processing company in Ethiopia. This cooperation supports their business development planning of a sorghum based food products, potential

markets, grain sourcing, standardizations and linkages to industrial milling of sorghum at the existing DINA milling facility near Adama.

At community level a "farmer to farmer" community-based and led seed ball transfer project entitled *caravane boule de semences* was funded by SMIL with key on-ground implementing partners. This innovation transfer effort allowed a much larger exchange of the seed ball technology between farmer cooperatives and actual smallholders in eastern Niger in which farmer associations, community leaders, local radio, and regional government were involved.

A food product showcase event was organized by Hawassa University to promote sorghum based food products which have been commercialized with small to medium enterprises (SME) in that region as well as presentations of unique products with future food product application potentials. The marketing director of the DINA Food Processing company was one key participant with particular interest in standardized teff and sorghum flour blends for injera.

The SMIL ME and its partner network developed and presented to USAID for the consideration of three proposals and budgets for climate smart agricultural and gender sensitive scaling, blended flour promotion and marketing in West Africa, and a sorghum milling exchange visit amounting to $3.65 million of strategic scaling investment.

The SMIL ME continues to develop formal partnerships with other implementing partners of USAID investment as a mechanism to strengthen the connectivity between our in-country research/technology network and other key USAID investments. One example of this was the formal MoU signed between our partners the Institut de Téchnologie Alimentaire (ITA) and the USAID-funded Entrepreneurship and Investment Project implemented by Winrock in Senegal. Specific women entrepreneurs commercializing sorghum and pearl millet food products developed with SMIL support will benefit from this cooperation in the Thienaba, Mewane, and Dakar zones.

Below is a summary list and description of the Phase 4,3,2,1 technologies.

Phase 4 technologies (demonstrated uptake by public/private sector)

1. ***Technology: Hybrids for commercial sorghum seed industry***

   Category: Plant and Animal Improvement Research
   Area of inquiry: Genetic enhancement
   Description: White sorghum hybrids P9511A/PRL020817 (K9058) registered and released with 5.76 t/ha yield performance for use in lowland growing areas of Ethiopia.
   Partnerships made: Partnership with a private company, ELFORA-Agro Industry PLC for seed multiplication. Collaborations with the Ethiopian Seed Enterprise (ESE), Regional Seed Enterprise (RSE), and private farms have been developed to support seed multiplication.
   Steps taken: Approximately 30 hectares of hybrid seed was multiplied by a private seed producer in Amhara region.
   Target country: Ethiopia

2. ***Technology: Direct release of Habrobracon hebetor adults for controlling the millet head miner***

   Category: Production Systems Research
   Area of inquiry: Production systems management
   Description: It was determined that the release of 800 parasitoids per 3km radius in the early panicle stage of the crop give a good level of control of the head miner. The 800 parasitoids correspond to 12 parasitoid bags, this will reduce the current numbers by (20%) for 3km radius. Given the current price

of $3.34/bag, a saving of $10 is expected per each release. Progress was made in the identification of numbers of H. hebtor adults needed per acreage of pearl millet for controlling the millet head miner.
Partnerships made: The technology has been transferred to farmer cooperatives in Niger
Steps taken: Discuss with donors and USAID value chain projects to support the dissemination.
Target countries: Senegal and Niger

3. ***Technology: Seed balls to reduce risk and improve yield in Sahelian pearl millet-based farming systems***

Category: Production Systems Research
Area of inquiry: Production systems management
Description: Seed balls are a sowing technique for semi-arid areas, especially aiming at the improvement of plant establishment with dry sowing. Seed balls represent a mixture of soil material, seeds, and additives (e.g., nutrients, pesticides). They aim at small-grain cereal cropping system with wide spacing (seed pockets).
Partnerships made: Fuma Gaskiya - Maradi, Niger (farmer organization); FAPAL - Louga, Senegal (farmer organization); INRAN – Niamey, Niger
Steps taken: Further sociological studies were carried out to better understand the farmer-to-farmer technology adoption mechanisms, number x type of training, extension support, etc. Initial investigations of the potential to apply this technology to sorghum production.
Target countries: Senegal and Niger

4. ***Technology: Registered germplasm with sugarcane aphid resistance for global use***

Category: Production Systems Research
Area of inquiry: Production systems management
Description: Seed balls are a sowing technique for semi-arid areas, especially aiming at the improvement of plant establishment with dry sowing. Seed balls represent a mixture of soil material, seeds, and additives (e.g., nutrients, pesticides). They aim at small-grain cereal cropping system with wide spacing (seed pockets).
Partnerships made: Fuma Gaskiya - Maradi, Niger (farmer organization); FAPAL - Louga, Senegal (farmer organization); INRAN – Niamey, Niger
Steps taken: Further sociological studies were carried out to better understand the farmer-to-farmer technology adoption mechanisms, number x type of training, extension support, etc. Initial investigations of the potential to apply this technology to sorghum production.
Target countries: Senegal and Niger

5. ***Technology: Improved sorghum variety***

Category: Plant and Animal Improvement Research
Area of inquiry: Genetic Enhancement
Description: An improved sorghum variety named *Merera* (ETSL 101371 (Acc. 212642)) has been officially released in Ethiopia with increased yield and disease-resistant characteristics.
Partnerships made: Oromia Ag. Research Institute, Bako Research Center, EIAR, and the National Research and Extension System (NARES)

Steps taken: Seed multiplication of this registered variety has been accomplished. Farmer plot trials/demonstrations completed and a large media publicity in vernacular radio and news has been organized in partnership with the regional government.
Target country: Ethiopia

6. ***Technology: Improved pearl millet varieties with key adaptation traits and increased yield.***

Category: Plant and Animal Improvement Research
Area of inquiry: Genetic Enhancement
Description: Improved pearl millet varieties (SL-28, SL-169, SL-423, Thialack 2) with increased yield of 2.1 to 3.0 tons / hectare.
Partnerships made: Farmer cooperatives, private seed companies
Steps taken: Farmer participatory plot trials, demonstrations, and seed registration for commercialization.
Target countries: West Africa

7. ***Technology: Improved pearl millet hybrid with key adaptation traits and increased yield.***

Category: Plant and Animal Improvement Research
Area of inquiry: Genetic Enhancement
Description: Improved pearl millet hybrid (TAAW) with increased yield of 3.5 up to 4.2 tons / hectare.
Partnerships made: Farmer cooperatives, private seed companies
Steps taken: Farmer participatory plot trials, demonstrations, and seed registration for commercialization.
Target countries: West Africa

8. ***Technology: Commercially packaged and branded sorghum and pearl millet based food products for urban, semi-urban and rural sales and consumption.***

Category: Production Systems Research
Area of inquiry: Added-value products and markets
Description: Commercialization of blended nutrient dense food products such as Lackiri, Degue de mil, Labduru, Dadin kowa, Grumeaux de mil, Tousme de mil garni au moringa, Farine pour bouillie, Labdourou de mil, Farine du sorgho, Farine de sorgho, Couscous de sorgho, Bassi de mil, Farine de mil fortifee, Mil senty / grumeaux pour bouillie, Mil senty couscous, Goumba delice, Extrudette which are marketed under multiple companies such as Entreprise de Transformation Cerealieres – ETC, Entreprise UNITAL, Groupement D'Interet Economique Bani-Bani, Groupement d'interet economique – EDEN, Bio-Nutri, Food Innovation Centers – Falwel, Tera, Sherkin Haoussa.
Partnerships made: Large and SME food processors, INRAN, Farmer Cooperatives. Green Yelda, CRS.
Steps taken: Continued technical support to women food processors and large food processing companies. Linkage and networking women entrepreneurs to additional financing opportunities and additional commercialization of new products.
Target countries: Senegal and Niger

Phase 3 technologies (made available for transfer)

1. ***Technology: Extruded sorghum- and millet-based food products***

Category: Production Systems Research
Area of inquiry: Added-value products and markets
Description: Formulas for extruded sorghum- and millet-based products that incorporate local plant products for the purpose of nutrient fortification have been developed. These formulations are being utilized in extruded infant cereal production.
Partnerships made: Purdue University, Moribeen/Western Niger (Tillabéri and Dosso) and Fuma Gaskiya/Eastern Niger (Maradi), McKnight Foundation, ISRA, CNRA, INRAN, Green Yelda, CRS, and an Italian NGOs called ACRA interested in scaling up of the Innovation hubs in rural areas
Steps taken: Continue testing on the products for nutrient delivery efficiency as well as product consumer feedback.
Target countries: Senegal and Niger

2. ***Technology: Sorghum and pearl millet based food products for urban and semi-urban consumers.***

Category: Production Systems Research
Area of inquiry: Added-value products and markets
Description: Commercialization of cereal blended nutrient dense food products packaged and marketed under brand names of Farine Katanaal (instant fortified cereal blend for children under 2 years), So'Fanny (instant cereal blend), Jaboot Thiakri, Jaboot Thiere, Arraw, Thiacry.
Partnerships made: Large and SME food processors such as Jaboot, So'Fanny, Purdue University, ISRA, CNRA, INRAN, Green Yelda, CRS,
Steps taken: Continued technical support to women food processors and large food processing companies. Linkage and networking women entrepreneurs to additional financing opportunities.
Target countries: Senegal and Niger

Phase 2 technologies (under field testing)

1. ***Pre-release of improved forage quality sorghum with bmr traits crossed with locally adapted and farmer preferred sorghum materials.***

Category: Plant and Animal Improvement Research
Area of inquiry: Genetic enhancement
Description: Three new varieties with increased forage quality stover yields 4.5 to 6 tons / hectare are being pre-released by INRAN for participatory evaluation with selected producers along with farmer led small ruminant feeding trials. Hegari/Macia//Sepon82 *bmr6,* Hegari/Macia//Macia *bmr6,* Hegari/CE-151-262-A1//CE-151-262-A1 *bmr6*
Partnerships made: Farmer Cooperatives, Regional Center of Excellence in Livestock
National Seed System, Ministry of Agriculture
Steps taken: Farmer participatory trials, national seed registration in process (2023), information sheets developed, production budgets developed of $850 per hectare, ongoing field showcasing to farmer cooperatives, NGO, and MoA actors.
Target countries: West Africa Sahelian Zone

2. ***Technology: Seed ball fabrication mechanization for men with mediocre investment capital***

Category: Production Systems Research
Area of inquiry: Production systems management
Description: Men will only invest in seed ball technology if working time demand is relatively low. Therefore, a mechanical device was constructed that can serve interested men as well as small local seed enterprises. The device allows for a throughput of several thousand seed balls per hour at medium (in the local sense) investment costs.
Partnerships made: Fleischle GBR, Vaihingen Enz, Germany
Steps taken: The mechanization option has shown to work under farmers' condition. However, local craftsmen were not able to copy it. It appears unlikely that the technology presented is worth investment. Much higher throughput per time is requested that can only be achieved by a motorized and more automated technology as used e.g., by Fleischle GBR. At the time being, independent efforts to mechanize seed ball production are underway: https://seedtheglobe.com/en/platform.html.
Target country: Niger

3. ***Technology: Seed ball fabrication mechanization for women with low investment capital***

Category: Production Systems Research
Area of inquiry: Production systems management
Description: The technology is based on an easy-to-construct frame that produces about 80 seed balls in one batch. It is designed particularly for women with low investment capital that need to sow more than a home garden surface.
Partnerships made: Fleischle GBR, Vaihingen Enz, Germany
Steps taken: The mechanization option has shown to work under farmers' condition. However, local craftsmen were not able to copy it. So, modifications need to be developed with craftsmen and farmers together, also to increase productivity. The presented tool did not sufficiently reduce working time needed in comparison to hand-made seed balls.
Target country: Niger

4. ***Pre-release of two new high yielding multipurpose Melanaphis resistant varieties for Haiti***

Category: Plant and Animal Improvement Research
Area of inquiry: Genetic enhancement
Description: Two new varieties are being pre-released by Chibas for participatory evaluation with selected growers before complete release (expected at the end of 2019). These 2 inbreds have been part of the extensive phenotyping and genotyping of all Chibas's inbreds carried with support of the USAID-SMIL project. Both showed the highest breeding value with genomic prediction and broad adaptation under the 11 environments in which the varieties have been evaluated under the USAID-SMIL grant/project.
Partnerships made : Prof Patrice Dion, Département de phytologie – IBIS, Université Laval - Canada National Seed System, Ministry of Agriculture, Natural Resources and Rural Development - Haiti
Steps taken: These varieties are now moving to production of "breeders' seed" so that in the 2 seasons of 2019 (spring and autumn) they can be evaluated by participating farmers (participatory evaluation)

before complete release (expected late 2019 or early 2020). Registration process is being initiated with the National Seed System (SNS) of the Ministry of Agriculture for these 2 varieties.
Target country: Haiti

5. ***Technology: Improved endosperm sorghum for protein quality and processing functionality***

Category: Production Systems Research
Area of inquiry: Added-value products and markets
Description: New sorghum hybrids under development combine high protein digestibility (HPD) mutation with waxy and heterowaxy (WX/HX) starch traits in hard endosperm for various food applications due to superior functionality and improved protein nutritional quality.
Partnerships made: Hawassa University, Texas A&M University, Ethiopian Institute of Agricultural Research
Steps taken: Field trials are being organized by EIAR for the future advancement of this hybrid for national registration. Production of 200-300 kg of grain to allow Hawassa University to continue food science testing and R&D of the grain for application in the Ethiopia food product market.
Target country: Ethiopia

6. ***Technology: Sorghum based food products for commercialization in Ethiopia***

Category: Production Systems Research
Area of inquiry: Added-value products and markets
Description: Food product recipes, milling specifications and standards for injera, cookies, pancakes, popped sorghum, as well as whole grain-based intermediate products such as couscous, *kinche*, popped sorghum and sorghum rice (*nifro*) are being refined and piloted with small scale women food processors.
Partnerships made: SME Food Processors
Steps taken: Characterization studies, continue testing, consumer preferences, piloting products with SME women entrepreneurs, and event showcasing to larger food processing companies.
Target country: Ethiopia

7. ***Technology: Sorghum based malting and adjunct for Ethiopian beer brewing industry.***

Category: Production Systems Research
Area of inquiry: Added-value products and markets
Description: Ingredient characterization, optimization of the malted and adjunct sorghums for brewing potentials of using locally improved sorghums on physicochemical and sensory characteristics of beer using novel sorghum malt and adjunct in brewing to support further commercialization of local sorghum grains in the brewing industry in Ethiopia.
Partnerships made: Ethiopian Brewing Industry
Steps taken: Characterization studies, needs assessment of brewing industry and potential use of sorghum based malt and adjunct, recommendations.
Target country: Ethiopia

8. ***Technology: Pre-release of a white colored anthracnose resistant improved sorghum variety.***

Category: Plant and Animal Improvement Research

Area of inquiry: Genetic enhancement
Description: An improved sorghum variety named *Jabaa* (ETSL 101259 (Acc. 200161)) in in prelease stage and will be registered in 2023 in Ethiopia with increased yield and disease-resistant characteristics.
Partnerships made: Oromia Ag. Research Institute, Bako Research Center, EIAR, and the National Research and Extension System (NARES)
Steps taken: Farmer level participatory evaluations, registered process initiated with government of Ethiopia.
Target country: Ethiopia

Phase I technologies (under research)

1. **Technology:** ***PCR-based tag system to accelerate sorghum breeding for disease resistance***

Category: Plant and Animal Improvement Research
Area of inquiry: Genetic Enhancement
Description: Develop a simple and efficient scored PCR-based tag system that will greatly speed breeding of disease-resistant sorghum cultivars, even in the absence of the pathogen.
Partnerships made: ISRA, INRAN
Steps taken: Development of the PCR-based tag system, training, and the arrival of Coumba Fall to TAMU for her Ph.D. training.
Target countries: Senegal and Niger

2. **Technology:** ***Striga resistance, stay-green, and drought tolerance alleles development and deployment***

Category: Plant and Animal Improvement Research
Area of inquiry: Genetic Enhancement
Description: Develop *Striga* resistance, stay-green, and drought tolerance alleles for smallholder demand driven product profiles in West Africa.
Partnerships made: ISRA, INRAN, INERA, ITRA
Senegal - Farmers organizations (RESOPP, ASPRODEB–Kaffrine and Kaolack, BAMTARE–Tambacounda); Food processors (women and NGO–KARITAS–Tambacounda); Industrials (Mamelle Jaboot, FNBS) and other research instituts (ITA)
Niger - Seeds companies including Hallal, Fusaa
Burkina Faso - FEPAB in the north-west, UGCPA in the south-west, AMSP in the east and G-NAAM in the north
Togo - OP Todlman grouping several farmers' organizations / location: Takpamba, Timbou, Goulougoushi, Naki-Est, Mandouri
Steps taken: Initial farmer field level trials and feedback on these materials to support the near-term registration and seed distribution.
Target countries: Senegal, Niger, Burkina Faso, Togo, (West Africa)

Environmental Management and Mitigation Plan (EMMP)

The SMIL ME has continued to ensure environmental compliance and confirm that the resources, responsibilities, and reporting (3R's) have been well defined and monitored throughout the lifetime of each research project implementation.

The in-country partners have continued to ensure that the research activities being funded comply with the national and USAID environmental compliance requirements as stated in the initial environmental evaluation.

The associated environmental monitoring and mitigation plans (EMMPs) for each research project have been supported by an EMMP web-based module, which facilitates reporting of actual environmental support visits by the environmental compliance staff and investigators of the implementing partner, as well as other relevant persons involved.

The planned activities under the current buy in include, in-country survey trips, desk research, interviews, and consolidation of an initial report with key recommendations. These activities align with the current prime award and EMMP.

Open Data Management Plan

The open data management plan has continued to be implemented and the SMIL ME has assisted each research project in the ongoing delivery of datasets into Harvard Dataverse and/or other relevant scientific databases that support their research. Each awardee and sub-awardee are submitting the link of each planned and in-progress dataset in our data collection/reporting system, the SMIL resource and reporting hub. In addition to the dataset, the data package includes metadata and other supporting documents; including codebooks that describe columns in the dataset, questionnaires used to collect data, informed consent forms, reports, and any other contextual documents. Research teams are ensuring that datasets are cleaned, and all personally identifiable information is excluded. Links to all data repositories are registered on the USAID DDL.

Governance and Management Entity Activity

All essential program implementation activities and essential coordination meetings with external partners were successfully carried out. The SMIL annual program review meeting was held again through a remote online platform over the course of 5 days. This structure provided ample time for project presentations, discussion, and internal review by the external advisory board. The focus was more aligned with in-country needs and successes. In Niger, the entire research team, women entrepreneurs and seed company end-users gathered in a coordinated manner in Niamey the capital. This allowed better internet connectivity and inclusion of our end-user team members. All project activities with downstream clients and other field activities were implemented using necessary safety protocols and travel authorizations.

International travel increased in fiscal year 2022. Visits to Senegal and Ethiopia, as well as visits from PIs to the US, allowed the greater SMIL team to collaborate more effectively. These visits were widely appreciated and provided excellent environments for considering research findings, project implementation planning, downstream scaling partnerships and interaction with future SMIL/USAID support scientists. These meetings also provided time and space to consider of the much longer-term view of key demands and needed developments along the sorghum and pearl millet value chains in the next five to ten years. The ME was also able to capture key video interviews to strengthen our communication initiatives. Additionally, outreach to stakeholders through a new website, social media, and monthly newsletters grew dramatically, tripling followers of the program.

Other Topics

Communications project

The SMIL ME developed a specific communications project leveraging in the Kansas State University Department of Communications and Agricultural Education linked with other private media and marketing services. The overall goal of the SMIL communications project is to "celebrate the success" of the SMIL/USAID investment in sorghum and millet, cultivate enthusiasm for future endeavors, and encourage the next generation of researchers/scientists in international development.

The SMIL communications project consisted of restructuring the SMIL website, project personnel interviews and research images, collection and display of video content, monthly newsletters, success stories, increased social media

engagement, targeted print documents, and other relevant media forms that support the key goals of the project. Information gathering and plans are being made to form a SMIL student and young career professional alumni platform to strengthen research collaboration and opportunities as well as networking. Training on personal branding with AWARD will soon be implemented, with nearly 40 women of SMIL participating.

Economic Impact Assessment

Several novel contributions were created in the economics project during FY 2022. The program led the development of the first section *Crop Adaptation and Improvement for Drought-Prone Environments*, a new book that will be published in November 2022. The first section of the book focuses on several social and economic issues about the adoption of climate adaptation strategies, the demand for value-added food products in the CORAF region and overall production and consumption trends. These topics are covered in six chapters published in an open-access monograph.

Secondly, the linkage between investment in agricultural research and development and impacts to broader society were documented in two manuscripts. Enhancing agricultural productivity growth is a key step to improving competitiveness and eradicating poverty rural areas in developing countries. While the Comprehensive African Agricultural Development Program (CAADP) recommended increased public spending in agriculture to induce productivity growth, the extent to which expenditures affect food productivity remains an empirical question. We assessed the effect of two government-spending measures: Agriculture Budget Share (BS) and Research Share of Agricultural GDP (RS) on agriculture total factor productivity growth (TFPG) in Africa. Using a panel fixed-effect estimator to control for the country-specific characteristics of twenty-eight African economies from 1991–2012, a marginal impact of 6.77% for RS on TFPG after seven years was found. However, the cumulative marginal impact of BS on TFPG is estimated at 7.21% over the eight years following the budget allocation. Our findings suggest that a BS of 14% and a RS of 15% are required for a country to double its TFPG in the following eight years. Therefore, additional, and continuous investment in research and development is required for a significant productivity growth, especially in Sub-Saharan Africa.

In another paper, we found that the U.S. Agency for International Development has invested limited funds in international agricultural research through U.S. universities. We presented a meta-analysis of impact case studies from this investment. The median net present value of economic impacts at purchasing power parity is PPP$8.4 billion compared to cumulative investment of US$1.24 billion over 1978-2018. About four-fifths of these economic benefits accrued to individuals with incomes under $5.50/day, and about 29 percent to those in extreme poverty. In addition to these limited case studies evaluating financial benefits and costs, we present several types of additional non-economic benefits.

New research was initiated in Ethiopia to evaluate the hypothesis that plant breeders focus on the traits that are the most important to consumers and processors. Field work in several Ethiopian states was collected and in the next fiscal year will be evaluated. The project will utilize the "Best-Worst" scaling approach to test the hypothesis.

Capacity building

Individuals trained under this project include:

85	Kansas State University	Ph.D.	Agricultural Economics

Presentations and publications

Hodjo, M. Dalton, T.J. and Nakelse, T. 2022. "Does Public Spending Trigger Agricultural Productivity Growth in Africa?" *Journal of African Development*. *In press*.

Hodjo, M. and Dalton, T.J. "Production and Consumption Trends of Dryland Staples in CORAF Nations." Chapter 1 in Crop Adaptation and Improvement for Drought-Prone Environments. Kane, Fonceka and Dalton eds. 2022.

Nakelse, T. and Dalton, T.J. "Consumer willingness to Pay for Millet-based Food Attributes in Niger" Chapter 5 in Crop Adaptation and Improvement for Drought-Prone Environments. Kane, Fonceka and Dalton eds. 2022.

Kane, N., D. Fonceka and T. J. Dalton eds. 2022. Crop Adaptation and Improvement for Drought-Prone Environments. Manhattan, K.S.: New Prairie Press.

Dalton, T. and K. Fuglie. "Costs, Benefits and Welfare Implications of USAID Investment in Agricultural Research through U.S. Universities." *Journal of Agricultural and Applied Economics.* 53(4): 461-479.

Dalton, T. 2022. "Proactive approach from USAID would enable universities to help head off hunger crisis: the world finds itself at the brink of another food crisis yet again. We shouldn't be surprised." Op Ed. *Des Moines Register. June 18, 2022. https://www.desmoinesregister.com/story/opinion/columnists/2022/06/18/usaid-world-hunger-proactive-approach-needed-head-off-crises/7634509001*

Future Directions

The second phase of the Fed the Future Innovation Lab for Collaborative Research on Sorghum and Millet is coming to an end in July 2023. Overall, the program has been very successful in the development of new seeds, agronomic interventions and value-added food products in Ethiopia, Niger, Senegal, and Haiti. For the next ten months, the program will concentrate resources to ensure that all products ready for uptake move forward along the product concept into stages six and seven while expanding some into stage eight. This will occur through dedicated investment of time and financial resources by the SMIL ME to remove any obstacles or impediments preventing popularization. For example, the SMIL ME sponsored a seed system workshop in Ethiopia that will be expanded to Niger and Senegal. The ME will coordinate a programmatic presence at the African Seed Trade Meeting to be held in Dakar in March 2023. At the same time, novel innovations will move from stage four into five to prepare for release especially for new sorghum with high protein digestibility, *Striga,* grain mold and drought resistance as well as dedicated forage varieties in both Ethiopia and West Africa.

The ME is conducting a sorghum value chain assessment for the USAID office in Madagascar. The objective of the assessment is multifaceted and includes institutional, agronomic and value-added investigations. The ME will work with a team of experts to evaluate challenges and opportunities for sorghum broken down by geographical region, production environment and whether the product is targeted at human food or animal feed and forage. This study will begin the first quarter of FY23 with an initial report expected shortly thereafter. Additional deep-dive studies will begin in the second quarter following the initial situational review.

In February and March of 2023, an annual wrap-up meeting will be scheduled in Ethiopia, Niger and Senegal. In addition to finalizing activities for 2023, the meetings will be an opportunity to take stock of technological, human and institutional capacity development created over the program's history. In addition, an innovation showcase will occur in each nation where the national program will invite stakeholders to assess the latest innovations in stages five and higher. This will also provide an opportunity for feed back into the national program and to establish priorities for future product profiles and innovation strategies.

The ME is active in the planning and development of the 2023 Global Sorghum Conference to be held in Montpellier, France from June 5-9, 2023. The program will send close to 80 collaborators, including students, to participate in oral, poster, and student section presentations. Track sessions will be developed that will present the philosophy of SMIL from problem identification and product profiling to discovery and adoption for seed, food product and agronomic innovations.

SMIL will come to an end on July 21, 2023. The ME will prepare a final report describing achievements, lessons learned, challenges and the opportunities for national, regional and global innovation in the rapidly evolving sorghum and millet sectors and will continue to advocate for investment in our focus countries.

Appendices

Appendix A – List of awards to U.S. partners – Phase-II

Title: Advancing improved functionality and protein quality sorghum hybrids for food applications in Ethiopia
Award: Texas A&M - Joseph Awika
Project Dates: 04/01/19 07/21/23

FY22 Funding Released:	$122,819.00
Total Funding Released:	$682,796.00
Overall Project Budget:	$734,629.00

Title: Genetic Enhancement of Sorghum to Promote Commercial Seed Supply and Grain Market Development in Ethiopia
Award: Purdue - Gebisa Ejeta
Project Dates: 04/01/19 07/21/23

FY22 Funding Released:	$0.00
Total Funding Released:	$348,185.00
Overall Project Budget:	$361,985.00

Title: Expanding Markets for Sorghum and Millet Farmers in West Africa through Strengthening of Women and Youth Processors and Nutrition-based Promotion of Products
Award: Purdue - Bruce Hamaker
Project Dates: 04/01/19 07/21/23

FY22 Funding Released:	$95,149.00
Total Funding Released:	$455,387.00
Overall Project Budget:	$525,570.00

Title: Phase II - Genetic improvement of sorghum for resistance to fungal pathogens
Award: Purdue - Tesfaye Mengiste
Project Dates: 04/01/19 07/21/23

FY22 Funding Released:	$214,260.00
Total Funding Released:	$756,937.00
Overall Project Budget:	$814,897.00

Title: Enabling Marker Assisted Selection for Sorghum Disease Resistance in Senegal and Niger

Award: TAMU – Clint Magill
Project Dates: 04/01/19 07/21/23

FY22 Funding Released:	$14,904.00
Total Funding Released:	$195,908.00
Overall Project Budget:	$198,354.00

Title: Sorghum Trait Deployment Pipeline for Improved Food and Feed Value
Award: Purdue - Mitch Tuinstra
Project Dates: 04/01/19 07/21/23

FY22 Funding Released:	$124,810.00
Total Funding Released:	$223,942.00
Overall Project Budget:	$258,942.00

Title: SAWAGEN: Improving Sorghum Adaptation in West Africa with a Genomics-Enabled Breeding Network
Award: CSU - Geoff Morris
Project Dates: 04/01/19 07/21/23

	CSU	KSU	Total
FY22 Funding Released:	$50,789.00	$0.00	$50,789.00
Total Funding Released:	$124,565.00	$166,219.00	$290,784.00
Overall Project Budget:	$189,647.00	$166,219.00	$355,866.00

Title: Genetic Enhancement of Pearl Millet for Yield, Biotic and Abiotic Stress Tolerance in West Africa (GENMIL)
Award: CSU – Geoff Morris
Project Dates: 04/01/19 07/21/23

	KSU-Hays	CSU	Total
FY22 Funding Released:	$0.00	$88,463.00	$88,463.00
Total Funding Released:	$83,839.00	$136,162.00	$220.001.00
Overall Project Budget:	$83,839.00	$216,888.00	$300,727.00

Title: Durable adaptation to aphid and drought for smallholder sorghum in the Americas
Award: CSU – Geoff Morris
Project Dates: 10/01/20 07/21/23

FY22 Funding Released:	$288,182.00
Total Funding Released:	$408,366.00
Overall Project Budget:	$595,930.00

Title: Agricultural Economics Research un the Sorghum and Millet Innovation Lab
Award: KSU – Timothy Dalton
Project Dates: 12/01/20 07/21/23

FY22 Funding Released:	$63,854.00
Total Funding Released:	$217,779.00
Overall Project Budget:	$277,583.00

Title: Sorghum and Millet Innovation Lab Communications and Branding
Award: KSU – Susan Schiff
Project Dates: 07/01/21 07/21/23

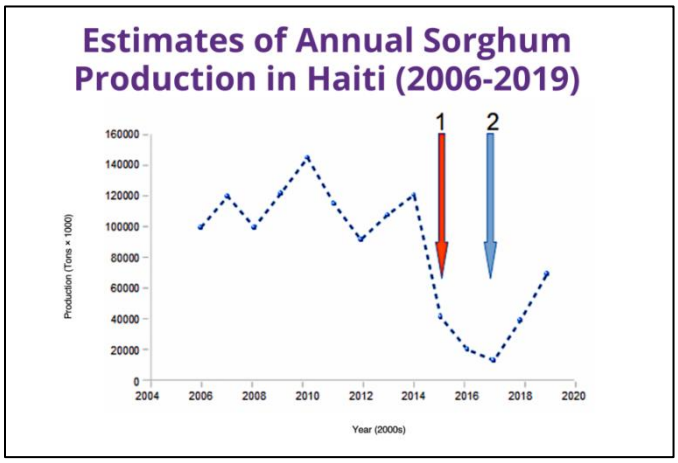
FY22 Funding Released:	$59,535.00
Total Funding Released:	$108,285.00
Overall Project Budget:	$108,285.00

Appendix B – Success stories

Seed sharing rescues a crop and leads to new pest-resistant technology

Haitian sorghum crop is now viable due to molecular marker discovery supported by 50 years of research. A research team supported by SMIL helped rescue the cereal crop sorghum with fifty years of global research and new technology.

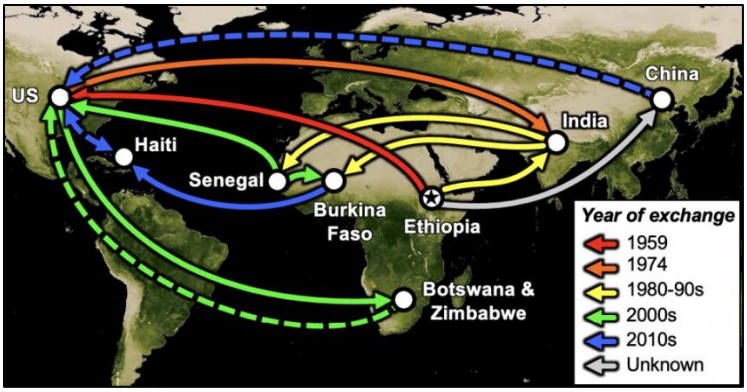
This research is reported in the February 11, 2022 issue of Science Advances as [The Recent Evolutionary Rescue of a Staple Crop Depended on Over Half a Century of Global Germplasm Exchange].



In Haiti, smallholder farmers saw the devastation that the sugarcane aphid can cause when it almost eliminated their sorghum crop in 2017. This was only two years after the aggressive new form of sugarcane aphid, M. sacchari, had been rapidly expanding and putting more than 90% of sorghum-producing areas of North America at risk.

To assist the Haitian farmers, the SMIL research team, led by SMIL Dr. Geoffrey P. Morris and Co-PI Dr. Gael Pressoir, partnered with the extensive and already established in-country sorghum-breeding program to develop a global germplasm exchange.

During the research, the team discovered a single gene naturally responsible for aphid resistance. When researchers combined the genomic scan technology with the research previously done, they were able to validate that the marker resistance to Melanaphis sacchari-1 (RMES1) gene was indeed a sugarcane-aphid-resistant locus and found throughout the global sorghum-breeding network.



The RMES1 gene variant, originally discovered in China, is a global rarity. However, RMES1 originated in Ethiopian sorghum lines, and through the research, it was understood that sorghum breeders across the globe prefer this germplasm. It was also discovered that the identified gene with sugarcane aphid, over time, had already been distributed across the sorghum-breeding platforms in three continents.

"As we pulled on the thread of history, we found a whole tapestry of how this success had come through the work of so many different scientists over the last 50 years. Fifty years of breeders, geneticists and entomologists were tracing it all the way back to farmers in Ethiopia, where this resistance likely originated a few hundred years ago," said Morris. "This research allowed us to understand the history behind the genetic evolution of the natural resistance to build the foundation for the use of today's genomic tools."

The molecular markers developed through this research for RMES1 facilitate the rapid conversion of existing farmer-preferred varieties to aphid-resistant varieties. However, that does not mean this gene will always be effective, as pests like the aphid evolve and create new variants. New discoveries are needed to stay ahead of genetic evolution of the aphid. "With the previous research on greenbug aphid, we know that pests can and will evolve to the products we use. With these genetic markers, we can continue to advance resistant varieties and hope to stay ahead of the natural evolution of the aphid," Morris said.

As a final step in the research, the sugarcane-aphid-resistance molecular markers were tested with four U.S. commercial seed breeding programs and three U.S. public sector breeding programs. This step confirmed that there was a match between the phenotype-based breeder classification and the molecular marker genotypes. With the molecular marker tool developed, breeders can efficiently convert the current farmer-preferred varieties to aphid-resistance varieties.

Sorghum is one of the most important crops in Haiti and worldwide because it is one of the most drought-tolerant cereal crops. Partnerships with researchers in Africa and Haiti were made possible with SMIL and funding from USAID. Success has translated into resilient seeds for low-income farmers in Africa and the Caribbean and improved profits for farmers in the United States.

Tim Lust, chief executive officer of National Sorghum Producers, said, "The work of SMIL certainly benefits the United States. Sorghum is a small industry worldwide and leveraging those dollars and the research and human talent is so important. With this project, when we look at sugarcane aphid and some of the challenges with it, the lessons we learned from this project are critical, from both a germplasm and plant viability standpoint. With this new molecular marker, we can quickly look at how that can be applied, and practical, hands-on research can be done in a timely manner that can get results. In all reality that would take us years and years to accomplish domestically by ourselves. And so, it's something that really allows us from a partnership role to evaluate new technologies and how those can be implemented quickly and what those opportunities really allow."

The project was a joint effort led by Dr. Geoffrey P. Morris and included a team of students and scientists from Kansas State University, Colorado State University, Université Quisqueya in Haiti, University of California-Berkeley, the HudsonAlpha Institute for Biotechnology, the Donald Danforth Plant Science Center, the United States Department of Agriculture, and the United States Department of Energy. For more about how molecular markers and decades of germplasm exchange saved sorghum, view a video.

Economists study impact of international agricultural research at U.S. universities

An economic analysis on the impact of international agriculture research and development conducted at U.S. universities over 40 years indicates that every dollar invested provides a return of $8.52 in economic impact. Kansas State University agricultural economist, Dr. Timothy J. Dalton reported results from a study of projects completed between 1978 and 2018 and funded by USAID.

The research looked at USAID projects representing an investment of $1.24 billion to support agricultural development and improve food security around the world. Those projects returned $10 billion in economic impact, according to Dalton.

Much of the work is done by agricultural scientists at U.S. land grant universities. "These university-funded programs positively impact the most vulnerable populations in low- and middle-income countries," Dalton reported. "Those living in poverty on less than $5.50 per day receive 78% of the research benefits, and nearly 30% of those receiving benefits live in extreme poverty on less than a daily net income of $1.90."

Dalton and Dr. Keith Fuglie, an economist with the USDA's Economic Research Service, co-authored a paper documenting the high return to investment in agricultural research and development. Their report is available in the June 30, 2022 issue the Cambridge University Press as Costs, Benefits, and Welfare Implications of USAID Investment in Agricultural Research through U.S. Universities.

"Agricultural productivity is one of the most powerful tools we have for promoting food security and equitable economic growth in low-income countries," Fuglie said. "When you raise agricultural productivity, you are improving the incomes and welfare of some of the most undernourished and poorest people in the world."

The authors found what they termed "high return investments" in such areas as integrated pest management technologies; new varieties of cereals and legumes; and in alleviating post-harvest losses through improved storage practices. "University investments in international agricultural research have delivered significant benefits for reducing poverty and improving nutrition for these low-income populations," Fuglie said.

Dalton said international research provides benefits to U.S. taxpayers as well. "We currently face insect pests in U.S. sorghum production that occurred in southern Africa in the 1980s, (and) in Latin America and the Caribbean during the early 2000s," he said. "When these pests appeared in the U.S., we were able to hit them head-on with the knowledge we generated for farmers in those other countries."

Dalton added that agricultural research targets two segments of populations in low-income countries: farmers who are just getting by, and consumers in urban areas who allocate 70-80% of their budget toward food, saying, "When we combine these two populations, we see that agricultural research is lifting broad populations out of poverty."

Dalton said, "That is what makes agriculture so much different than many other investment alternatives. Investment in agriculture affects the population broadly through higher incomes or cheaper food. Investment in agricultural research and development takes time, (but) persistence pays." For more about evaluating the benefits of the U.S. tax payer investment with international agricultural research, view a video.

Seed Ball Technology Improves Sahelian Pearl Millet and Sorghum Farming

The Sahel region of Africa is one of the harshest cropping environments in the world. Sahelian farmers have limited resources, income, and access to inputs such as fertilizer and water. This makes the region ideal to introduce new technology advancements to help smallholder farmers with planting techniques to increase the pearl millet crop yield rate. The SMIL Seed Balls project, Enhancing the Yield Effect in Pearl Millet and Sorghum and Disseminating the Technology in West Africa, developed seed ball technology to increase average yield up to 30% to provide opportunities for entrepreneurs (especially women) and increase income for smallholder farmers.

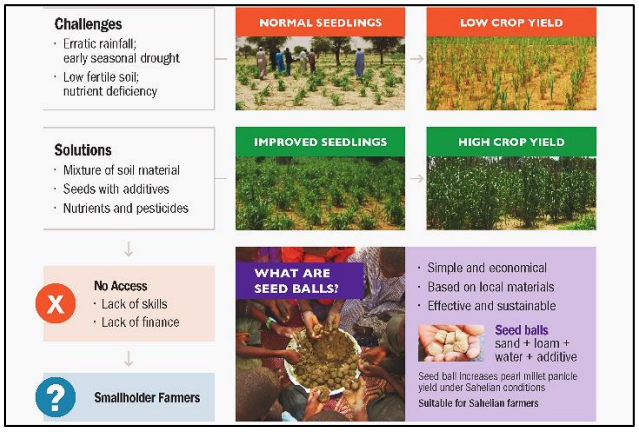
SMIL efforts are led by principal investigator Dr. Ludger Herrmann, professor at Institute of Soil Science and Land Evaluation, Soil Chemistry, and Pedology, at the University of Hohenheim (Universität Hohenheim in Germany).

A seed ball is a sowing technique for semi-arid areas, aimed at the improvement of plant establishment with dry sowing. Seed balls, originally studied in the 1970s, create a micro-environment that can capture moisture and make nutrients more valuable. Some literature references their use in Australia for range land farming and in Eastern Africa for range land amelioration, but no real research on seed ball use was conducted.

SMIL explored this technique after some pre-studies and a first test had been conducted. The project is economically important because pearl millet and sorghum are staple crops in Niger and Senegal. Pearl millet and sorghum are already adapted to the climate and can grow in really difficult conditions. These are also traditional crops in the region, ingrained in the culture and traditions of the people who live in West Africa, and are vital cereal grains women use to feed their families. Seed balls utilize locally available products, such as soil, wood ash, urine, seeds and pesticides. Because they are available and are needed in smaller quantities, they are a low-cost and low-risk option with high rewards."

"A farmer in the Sahel has a great risk in applying fertilizer, because if there is a drought and the crop fails, they have spent money with no outputs," said Dr. Herrmann. "Seed balls can be a solution because we introduced minimum amounts of fertilizer to support the plant during the first few weeks of growth. Then the crop will grow. The farmer will see that and decide to add the additional fertilizer. In this case, the seed balls have greatly reduced the risk of economic loss."

Lowering risk is vitally important, particularly for female farmers. The more fertile land is typically owned by their husbands. Those sections are close to villages and seeds are planted often right before the rainy season for the best chance



for success. This leaves the women's land to be planted early, when any moisture may still be weeks away and are often far from the villages.

Dr. Hermann explains, "Women are mostly planting their fields in the dry season and every rain you miss, you miss the chance of biomass production and yield. With yields already low, the women don't have to invest much money into this technology because it is made with local resources." With this technology the seed ball can stay protected underground, where the nutrients it needs can wait for moisture, while mitigating seed loss due to pests such as rodents, birds and termites.

Dr. Hannatou Moussa Oumarou, researcher at INRAN and Co-PI of the Seed Balls project, explained how the seed ball gives the pearl millet and sorghum a much stronger start: "Planting seed balls increases how many plants germinate because there is nitrogen (N), phosphorus (P), potassium (K), and wood ash with them. That helps the plants grow, and at the end, the yield is better than the normal conventional sowing. During a drought, the seed ball is better than conventional sowing. The seed balls gave smallholder farmers something to harvest during a drought."

Seed ball technology is also very adaptable to each farmer's needs. Every village can have a different soil composition and different pests they are protecting against. Because seed balls are all made locally with native ingredients, they can be customized to the specific needs of the local farmers.

According to Dr. Charles Ikenna Nwankwo, a scientific researcher at the University of Hohenheim, "One good thing about seed ball technology is that it is quite flexible. For instance, where you have challenges with low soil nutrients, you can introduce an additive that will improve the nutrients of the soil. If you have a challenge with insects, you can add an insecticide."

To increase farmer acceptance and use of the seed ball technology, Dr. Moussa Oumarou leads the efforts to train local farmers on the seed balls. In joint effort with Dr. Ikenna Nwankwo, she started training a small area of farmers, particularly women, and has now seen those women she trained become trainers to other women in their villages.

"I am excited to work with subsistence farmers and especially women farmers. We started training a small group of farmers and told them just to come and see what we were working on. The farmers wanted to teach more people as they saw their farms succeed! There were many who took the seed balls and sowed them in their region to see how it works," said Moussa Oumarou.

"Pearl millet is a traditional crop grown in these countries. The centers of genetic origins are located here," said Dr. Timothy J. Dalton, SMIL director. "So, they're extremely rich and the population is tuned into them. Losing millet would be detrimental to these countries. We see pearl millet as frontier frontline crops, so the investment is absolutely critical. The seed ball planting technique has allowed these smallholder farmers, especially the women, to plant, start and grow a successful crop of the pearl millet. With a successful crop, smallholder farmers have the ability to feed their families and sell for economic income."

The advancements made in this project and the lives changed are a result of a group effort coordinated by SMIL. Other partners in this effort are the Gaskiya Federation of Maradi Farmers Unions (Fédération des Unions de Producteurs de Maradi Gaskiya - FUMA Gaskiya), FAPAL (farmer organization), and the Federation of Unions of Peasant Groups of Niger (Fédération des Unions de Groupements Paysans du Niger - FUGPN Mooriben). This collaborative effort has been successful and will only continue to help more farmers in the future.

In September, over a thousand producers participated in a seed ball caravan in Maradi, Niger, learning about the seed ball technology and how to implement it in their communities. For more about how seed ball technology improves Sahelian pearl millet and sorghum farming, view a video.