Federico Diaz

BREEDING ACHIEVEMENTS FOR ACCELERATING THE DEVELOPMENT AND ADOPTION OF EARLY, RESILIENT, AND NUTRITIOUS POTATO AND SWEETPOTATO VARIETIES

Annual Report

January 2021

Breeding Achievements for Accelerating the Development and Adoption of Early, Resilient, and Nutritious Potato and Sweetpotato Varieties

Annual Report

January 2021

Lead Institution: International Potato Center (CIP)

Director: Barbara Wells

Address: Apartado 1558, Lima 12, Peru

Phone: (51) (1) 349-6017/349-5783

Fax: (51)(1)349-5638

Website: www.cipotato.org

Responsible persons

Hannele Lindqvist-Kreuze: h.lindqvist-kreuze@cgiar.org

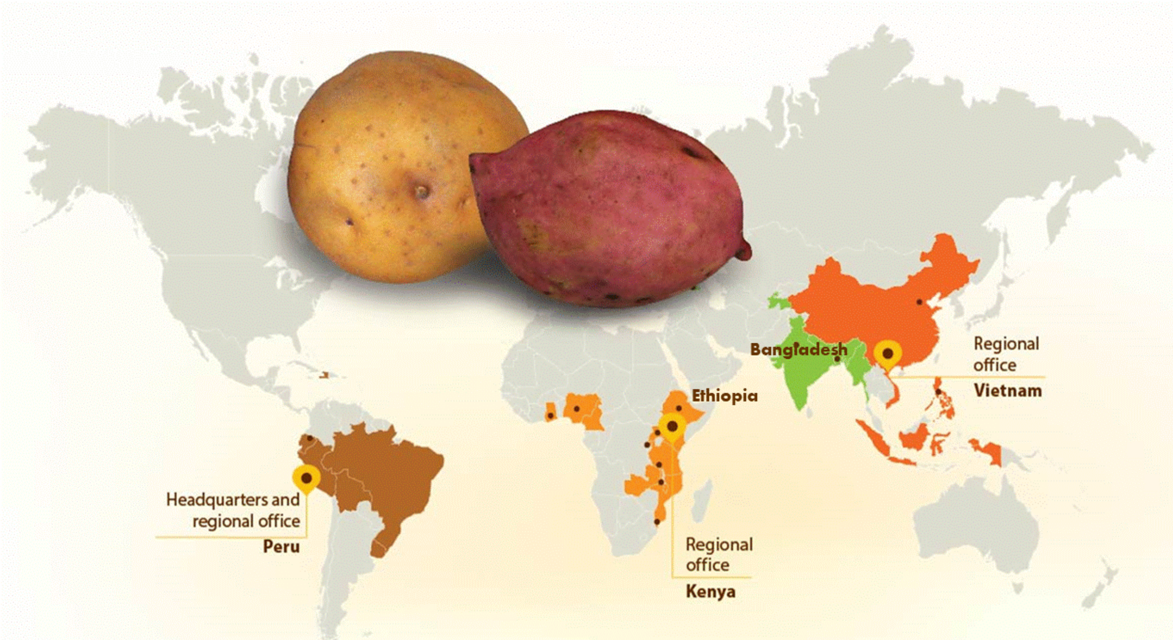
Wolfgang Grüneberg: w.gruneberg@cgiar.org

Designation: Plant Breeder

Place and Role: CIP Headquarters

Cover Photo: Harvesting H1 hybrid population in the humid tropics of the Peruvian Amazon at Satipo for product profile of high-iron orange-fleshed sweetpotato in the arid Pacific coast agro-ecology with a climate similar to the Mediterranean. (Photo: Federico Diaz)

COUNTRIES WHERE THE PROJECT WORKS



PROGRAM PARTNERS

- Bangladesh: Bangladesh Agricultural Research Institute; Bangladesh Agriculture University; Prodipan; Gana Unnayan Kendr
- Ethiopia: Ethiopian Institute of Agricultural Research
- Kenya: Kenya Agricultural and Livestock Research Organization; Kenya Plant Health Inspectorate Service; Agricultural Development Corporation–Molo; University of Nairobi; Egerton University; Stokman Rosen (private sector for tuber seed multiplication)
- Peru: Instituto Nacional de Innovación Agraria; Asociación Pataz, Fovida, Yanapai

ACRONYMS

BARI	Bangladesh Agriculture Research Institute
BAU	Bangladesh Agriculture University
BMGF	The Bill and Melinda Gates Foundation
BTI	Boyce Thompson Institute
CIP	International Potato Center
DFID	Department for International Development
EIAR	Ethiopian Institute for Agricultural Research
EiB	Excellence in Breeding
Fe	Iron
GG	Genetic gains
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
HQ	Headquarters
HZPC	A Dutch potato breeding company
INIA	Instituto Nacional de Innovación Agraria
LB	Late blight
NARS	National agriculture research system
OFSP	Orange-fleshed sweetpotato
PFSP	Purple-fleshed sweetpotato
PPP	Public–private partnership
PVS	Participatory varietal selection
RTB	Roots, Tubers and Bananas (a CGIAR Research Program)
SNP	Single-nucleotide polymorphism
SOP	Standard operating procedures
SP	Sweetpotato
SSA	Sub-Saharan Africa
UNAP	Universidad Nacional Del Altiplano Puno
USAID	United States Agency for International Development
WUR	Wageningen University and Research

GLOSSARY

Anemia	Having a lower-than-normal number of red blood cells or quantity of hemoglobin
Bioavailability	Degree to which a nutrient can be absorbed and utilized from the dietary source
Biofortification	Process of increasing the micronutrient content of a food crop through selective breeding
Genetic gains	Expected or realized change in average breeding value of a population over at least one cycle of selection for a particular trait or index of traits
Iron deficiency	Decreased total iron body content
Product profile	Means to identify appropriate traits for prioritized breeding zones or customer segments

TABLE OF CONTENTS

Photos

1. EXECUTIVE SUMMARY

With funding from the United States Agency for International Develop (USAID), the International Potato Center (CIP) is implementing a single breeding program that delivers genetic gains (GG) on two crops, potato and sweetpotato (SP). The USAID investment contributes to potato-breeding activities in Kenya, Ethiopia, Vietnam, and Peru and to SP breeding in Bangladesh and Peru. The goal of the activity is to develop new and better potato and SP varieties for smallholder farmers in order to improve their livelihoods. These new varieties are being developed using the principle of breeding product profiles and according to the breeding program improvements shared with the Excellence in Breeding (EiB) target-specific markets and the target population of environments. In the medium term, smallholder farms in Asia, Africa, and Latin America and the Caribbean will have access to new, stable, and high-yielding potato and SP varieties that are resilient to disease and climate change and are rich in iron (Fe) and vitamin A + Fe, respectively. This enables these farmers to improve their capacity to manage constraints affecting sustainability and household economy. The impacts of new varieties, when accompanied by functioning seed systems, successful crop management, and competitive value chains, can reduce poverty and malnutrition and enhance food security, farming, and food system resilience.

CIP's global potato and SP crop improvement programs emphasize improvement and dissemination of populations, whereas variety selection and releases from improved populations are carried out in cooperation with partners in target countries. Current breeding pipelines are closely aligned with market segments delivering single product profiles per market segment. The first-generation product profiles were developed with EiB support and will be improved based on the intel gathered through socioeconomic surveys. Modernization of the breeding program has advanced and, with the support of EiB, the program has focused on the breeders' equation and increasing the GG in various ways. Significant advances have also been made in improving the data management through the use of modern statistical field design and methods in data analysis.

One of the most important traits of potato is its nutritional content, particularly Fe. Our recent study on the bioavailability of Fe showed that 24.8% is absorbed from yellow-fleshed potato, which is remarkably high compared with other plants. In contrast, people absorb only about 2–10% of the Fe in most vegetables, or 3–8% of the Fe in beans. Therefore, potato has the potential to become a biofortified crop to combat anemia in countries/regions where potato consumption is relatively high, such as Rwanda, India, Bangladesh, and Peru. Sweetpotato breeding has experienced a real breakthrough with a heterosis or hybrid breeding strategy whereby significant GG of up to 132% were obtained by combining two different heterotic genepools. Initial field results confirm that hybrid breeding has the potential to revolutionize SP breeding and that hybrid breeding can surpass the gains of 36 years of traditional breeding within just five or six years. CIP's national partners are expected to lead the registration of the first commercial SP hybrid clones as early as 2022.

II. FOCUS COUNTRY KEY ACCOMPLISHMENTS

a. Bangladesh

The Global Hunger Index[1] ranks Bangladesh currently at 88th out of 117 qualifying countries. Prevalence of malnutrition is higher still than in countries like Nepal, Cambodia, Ethiopia, and Uganda due largely to its poor dietary quality[2,3]. Expanding consumption of nutrient-dense crops and animal source proteins is a priority for the Bangladesh government. Aligning with governmental policies, the International Potato Center (CIP) is collaborating with Bangladesh Agricultural Research Institute (BARI) to develop and disseminate nutrient-dense, biofortified orange-fleshed sweetpotato (OFSP). In 2020 CIP, in collaboration with Prodipan and Gana Unnayan Kendr (two national NGOs), produced 1,125,000 and 720,000 vine cuttings through vine multipliers of promising BARI-released OFSP varieties: BARI SP 4, BARI SP 8, BARI SP 12, and BARI SP 15. The efforts engaged 5,100 farmers in northern and southern Bangladesh to grow SP in home gardens where a total of 280 tons (t) of SP were produced in a pilot study. Most of the OFSP produced has been consumed on farm due to food supply crisis during the COVID-19 pandemic. The dissemination program is linked with a project led by the CGIAR Research Program on Roots, Tubers and Banana (RTB), namely Development and Delivery of Biofortified Crops Program at Scale, funded by the Department for International Development (DFID) (No. 1394-DFID), as well as the Strengthening Food System Resilience in Asia's Mega Deltas with Salt-tolerant Sweetpotato and Potato, funded by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)/BMZ (No. 1350-GIZ0).

Staff. The CIP–Bangladesh SP component has matured in 2020. One breeder and two research technicians were appointed in 2020, and one senior scientist is working with SP and potato. **Equipment.** Two –20˚C deep freezers and two oven dryers were purchased. **Variety and advanced breeding trials.** Under a CIP-BARI collaboration, 12 trials in the districts of Khulna and Satkhira were conducted with five released varieties and 120-day harvest. BARI SP 12 yielded 24.6 t/ha, followed by BARI SP 4 (19.6 t/ha), BARI SP 8 (19.4 t/ha), BARI SP 7 (17.4 t/ha), and BARI SP 6 (15.4 t/ha). Two farmers field days planned for March 2020 were postponed due to COVID-19.

Early breeding stages—preliminary yield trials. After three years of field evaluation of 3,320 genotypes derived from CIP true seed introductions, BARI selected 11 genotypes in 2020 based on two locations, Bogura and Gazipur. These will enter advanced OFSP breeding stages in 2021. To fit SP into present cropping patterns, CIP and BARI have been targeting very short crop durations (of 90 days from planting to harvest) since 2018. Elite crossings from CIP's headquarters (HQ) OFSP hybrid population H0 were introduced and multiplied. Observation trials were established at BARI stations at Jamalpur and Bogura in December 2020 (5,000 genotypes); the trials will be harvested in April 2021. Moreover, observation trials for purple-fleshed sweetpotato (PFSP) have been established at BARI research stations at Gazipur and Debigonj, based on CIP true seed introduced in December 2020 with 956 genotypes. The PFSP is not yet available in Bangladesh.

BARI has provided CIP 2 acres to conduct crossing and vine multiplication. In September 2020 CIP signed a memorandum of understanding with Bangladesh Agricultural University (BAU) in which they

1. Bdnews24.com. 2019.https://bdnews24.com/economy/2019/10/16/bangladesh-ranks-88th-on-hunger-index-above-india
2. FAO. 2014. Food and Nutrition Paper: Bangladesh. Food and Agriculture Organization of the United Nations, Rome, Italy, p19.
3. icddrb. 2020. A brief guide to malnutrition and its impact globally and in Bangladesh. https://www.icddrb.org/news-and-events/press-corner/media-resources/malnutrition

agreed to select (1) suitable techniques to cultivate SP the year around, (2) 90-day maturity SP will be developed, and (3) GG studies with released SP varieties will be conducted. We are aiming at a vine multiplication on scale for decentralized vine multipliers and through NGO and public–private partnership (PPP) methods.

b. Kenya

CIP is working to expand and modernize breeding operations in Africa toward a market-demand approach to increase GG and varietal adoption, which is supported by USAID. Potato-breeding goals in Africa include the following: (1) Develop durable resistance to predominant diseases—late blight (LB), virus, bacterial wilt); (2) develop stable yields and quality with less water and under warmer temperatures; (3) improve nutritional and market traits; and (4) develop varieties matching cropping system requirements. The program operates from a regional breeding hub in Kenya, with Ethiopia as a secondary site under CIP's Potato Agri-food Systems Program, which targets African highlands. The regional potato-breeding effort is based on rational use of adapted African potato germplasm to exploit the power of heterosis and increase diversity by introducing new alleles from exotic germplasm into elite breeding populations producing novel locally adapted potato varieties in partnership with several national institutions. As a result of a number of selection cycles in Kenya, advanced clones of potato adapted to the African highlands were selected. Preliminary results revealed high-yielding advanced materials (20% over the best local check), earliness, LB resistance, and excellent quality attributes. Modern varieties to be released will be more robust and targeting market-demanded traits than those currently grown, striking a balance in addressing farmers' limited ability to purchase inputs and meeting diverse market demands. As part of the improvements being implemented by the potato breeding program in Africa in the last two years, (1) a comprehensive investment case was developed for fast-cooking, early-maturing multipurpose potato with short dormancy and the good-tasting, medium-maturity iron (Fe)-biofortified table potato; (2) our operational capacity has increased significantly by the improvement/construction of greenhouses and warehouse for breeding seed multiplication and storage; (3) substantial breeding progress was achieved, increasing the likelihood of success using p-rep designs, data analysis with mixed models, and optimization of multistage selection; (4) embracing Excellence in Breeding (EiB) and the Crops to End Hunger initiatives; and (5) increasing the engagement with national partners through a breeding network in capacity building and sharing germplasm for variety development and population improvement.

Furthermore, with the support of EiB, potato product profiles across African countries have been defined, increasing our market knowhow. We hope that this approach will provide much needed "market signals" on preferred traits to drive future breeding priorities. To date, the Breeding Product Pipeline at the late product testing consists of 103 clones with potential to be released as variety or used as parents for a new round of elite crosses.

One future challenge is the rate of GG expressed under farmer management in the form of farmer- and market-demanded product profiles and average area-weighted age of varieties in farmers' fields that are the current high-level performance metrics used to evaluate CGIAR breeding programs and beyond.

c. Ethiopia

Potato ranks first among all other horticultural crops grown in Ethiopia in area of production, representing 60% of the total area covered by root and tuber crops and 28.5% of all horticultural crops added together. The actual released varieties by the potato-breeding program fetched a mean total tuber yield GG of 0.14 t/ha, and LB severity score reduction rate of 0.31% per year during the past 25 years[4]. The Ethiopian potato-breeding program has a long-standing working relationship with CIP's sub-Saharan Africa (SSA) region, which was the major source for germplasm of a large genetic pool for selection-based improvement activities in addition to technical trainings. As part of the regional breeding strategy, breeders from CIP and the Ethiopian Institute of Agricultural Research (EIAR) have used a wide genetic resource to develop improved populations adapted to local conditions. The aim is to generate elite materials with tolerance to biotic and abiotic stresses as candidate varieties that can be easily adopted by farmers or used as parents.

The variety development strategy has followed an innovative gender-disaggregated participatory varietal evaluation (PVS) approach to identify the most promising clones, increase adoption, and align with end-users/markets. Clones combining high yield, farmers' preferred traits, and organoleptic quality were identified together with farmers. We observed that women prioritized disease resistance, thick and strong stems, and long storability, whereas men preferred traits like medium maturing, vigor, and white flowers that take a while to drop. This provides great decision support for the breeding program for better defining breeding targets. At present, the potato-breeding program is focusing on crossing of elite parents, and the breeding pipeline holds a number of clones in different stages aligned with the predefined product profile. A novel locally adapted potato variety selected in Ethiopia is about to be released. A series of trials were implemented in 2020. Despite COVID-19 restrictions, substantial progress was achieved in implementing an accelerated breeding scheme at early selection stage from Ethiopian crosses. We also made progress in evaluating advanced selected potato clones for high yield in lowland and mid-altitude agro-ecologies, preliminary evaluation of selected clones from SSA crosses for LB and yield in highlands of Ethiopia, and implementation of new crossing blocks. Testing and implementing of new tools remain competitive in breeding; therefore CIP has provided a vital support to the national potato program in Ethiopia.

A workshop was organized to define product profiles targeting different markets in Ethiopia to ensure that the breeding goals will be defined based on increased awareness of market needs and opportunities. Additional capacity building and backstopping were carried out on the following: (1) characterization of selected parents with desirable complementary features; (2) accelerated phenotypic selection complemented with molecular markers; (3) use of new statistical design such as p-rep; (4) data analysis with mixed models; (5) optimization of multistage selection; (6) biofortified potato breeding; and (7) release of market-oriented products. The national program has increased its capacity on qualified personnel and infrastructures that maintain the breeding operations. At present, EIAR's potato breeding program has five trained plant breeders with good practical experience on conventional crossing at PhD and MSc levels, three agronomists, three tissue culture experts, a pathologist, and an entomologist working fully and partially on potato. Nonetheless, the program still lacks critical modern physical facilities.

---

4. Wassu Mohammed Ali. 2017. Genetic gain of tuber yield and late blight resistance in potato in Ethiopia. *East Af.J.Sci.* 11(1):1–16.

d. Peru

Fe and zinc (Zn) deficiencies are the most common micronutrient deficiencies worldwide. They disproportionately affect the poorest and most vulnerable populations in resource-limited settings, negatively impacting health, child development, and economic activity. Anemia continues to be a chronic problem in Peru, affecting 43% of children and 21% of women of childbearing age in rural areas of the highland Andean regions. Crops that have been biofortified with Fe and Zn are a cost-effective strategy to mitigate deficiencies of these two minerals. CIP's potato breeding program has been systematically working on improving the micronutrient content of potato since 2012, and obtained large GG for Fe (29%) and Zn (26%)[5].

In collaboration with Peruvian NGOs Yanapai and Asociación Pataz, candidate varieties from these populations were tested following the participatory scheme with smallholder farmers. The best 12 tetraploid advanced biofortified potato clones were in the field trials in the 2019–2020 growing season in northern, central, and southern Peruvian highlands. In each location, there was one trial for the identification, adaptation, and efficiency protocol corresponding to the distinct, uniformity, and stability testing required for variety registration and release. Trials were also conducted for PVS with the local communities. The aim was to select the two best clones according to their field performance, culinary quality, and nutritional content, for their subsequent evaluation and launch as varieties. The COVID-19 emergency complicated the visits planned for the national variety release authority, Instituto Nacional de Innovación Agraria (INIA) as well as complete data collection from the PVS trials according to the plan. The trials were overseen by consultants, who despite all difficulties managed to harvest the tubers in May 2020. CIP coordinated the transport of the tubers to Huancayo station and to Lima for processing and nutritional content analysis. Although COVID-19 made it impossible for CIP researchers to participate in the field evaluations, the work continued thanks to the local partners in each community. All field work was conducted following health and safety protocols specifically designed for the emergency situation. The analysis of the results from the 2019–2020 campaign will be finalized by March 2021, when the nutritional content analysis will be ready. These results are crucial in selecting the best clones for variety registration trials and narrowing down the number of clones for the next trials to reduce the activity costs. For the 2020–2021 season, the trials were planted in collaboration with the Anemia Cero project in northern Peru, a new NGO collaborator, Fovida, in central Peru, and INIA–Puno in south. The results from the PVS trials and nutritional content analysis will be shared with the stakeholders in a product advancement meeting in May 2021. The meeting will showcase current status in order to both select the best performing clones for variety release and raise interest among potential funders for seed multiplication. Tuber seed of selected potato clones with high Fe content were distributed to the beneficiaries in the potato-based production systems in high Andean regions of Peru (Curgos and Julcán districts, Province Sanchez Carrion, Department of La Libertad) and to scale agricultural and nutrition innovations in coordination with social protection and economic inclusion programs. Three of the biofortified potato clones that were planted last year in the area (CIP312721.074, CIP312721.245, and CIP312725.047) were distributed. This is a collaborative action with a bilateral project, Towards Eliminating Anemia in the High Andes: Linking Social Protection with Agriculture and Nutrition Interventions for Scaling, funded by the Canadian International Development Research Center.

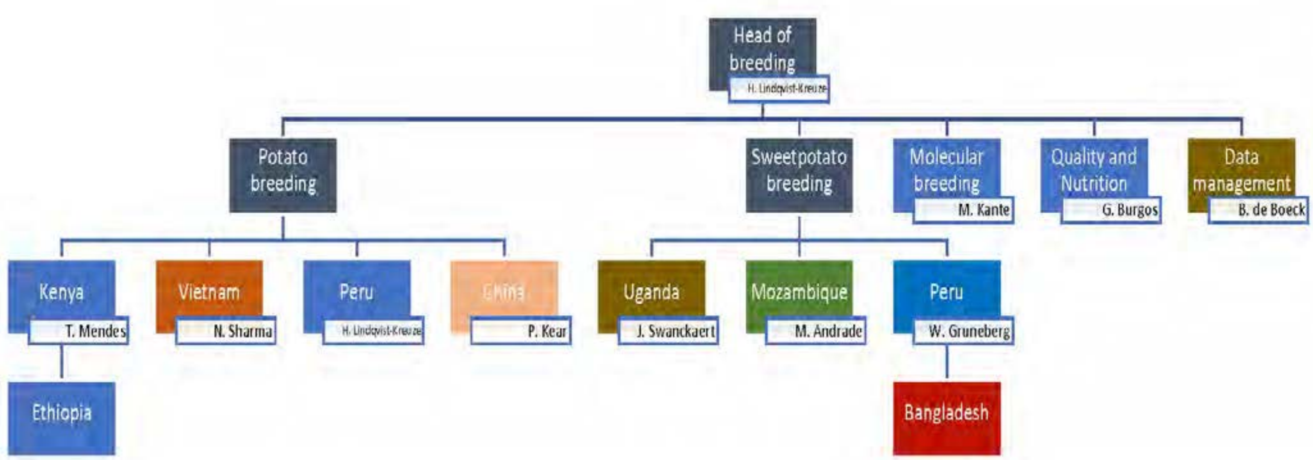
---

5. Amoros, W., Salas, E., Hualla, V., Burgos, G., De Boeck, B., Eyzaguirre, R., zum Felde, T. and Bonierbale, M., 2020. Heritability and genetic gains for iron and zinc concentration in diploid potato. *Crop Science* 60(4): 1884–1896. https://doi.org/10.1002/csc2.20170.

III. RESEARCH PROGRAM OVERVIEW AND STRUCTURE

CIP has recently reorganized its genetic improvement efforts into a single breeding program that delivers GG on two crops, potato and SP. Under new leadership, the breeding program has recently adopted a more integrated and coordinated approach across both crops, and is pooling resources and efforts toward modernization and developing shared technologies and capacities at scale. The breeding operations are led from CIP's HQ in Lima, Peru, with significant amount of decision-making and activities taking place in breeding hubs located in Africa and Asia (Fig. 1). The HQ breeding hub runs potato- and SP-breeding activities and distributes both early and late stages of breeding germplasm to the regional hubs as well as to the national agriculture research system (NARS) programs globally according to the demand. HQ is also hosting the quality and nutrition laboratory, coordinates the molecular breeding activities, and provides data management and statics support. The expertise in these science disciplines is available for all the breeding hubs. Besides HQ, potato-breeding hubs are located in Kenya, Vietnam, and China. The Kenya hub coordinates the African potato-breeding network and provides germplasm through the phytosanitary frameworks of the Kenya Phytosanitary Health Inspectorate Service in the African region. In 2020 CIP also had breeding staff in Ethiopia, but as of 2021 the activities will focus on Kenya, and the links to the other countries will be exclusively through NARS partners. The Vietnam hub, which is envisaged to serve India, Indonesia, and the Philippines as well, was established in collaboration with HZPC, a Dutch potato breeding company and with the support of Syngenta Foundation for Sustainable Agriculture. The Vietnam breeding hub is supported by crosses made in Peru. The China breeding hub is exclusively funded by the Chinese government. Besides HQ, SP breeding hubs are in Uganda, Mozambique, and Bangladesh. The African SP hubs are largely supported by The Bill and Melinda Gates Foundation (BMGF), with some specific activities in Uganda co-funded with USAID. The newly established Bangladesh hub at BARI's facilities is co-funded by GIZ, DFID, and USAID, and is receiving strong backstopping and capacity building from CIP HQ.

Figure 1. CIP's breeding program structure and the lead scientists in each area. The Vietnam breeding hub (orange) is cofunded by Syngenta, a PPP agreement with HZPC, and USAID. The Mozambique breeding hub (green) is funded by BMGF, whereas data management and the Uganda breeding hub (brown) are cofunded by BMGF and USAID. The Bangladesh hub (red) is cofunded by GIZ and USAID. The blue hubs and areas are cofunded by CRP-RTB and USAID.



IV. THEORY OF CHANGE AND IMPACT PATHWAY(S)

PROBLEM STATEMENT	The adoption of potato and sweetpotato varieties depends strongly on end-user preferences, and the availability of such varieties hinges on the efficiency of the breeding programs and their ability to generate genetic gains in the key traits.

INPUTS	ACTIVITIES	OUTPUTS	SHORT-TERM OUTCOMES	MIDTERM OUTCOMES	LONG-TERM OUTCOMES
• Human resources in the 10 operational units across the breeding program (see Fig. 1) • Greenhouse and field facilities in the breeding hubs • Laboratories for processing, quality, and nutritional analysis, cytogenetics, and true seed processing • Efficient genotyping and phenotyping systems • Database infrastructure	• Development of product profiles for the market segments • Design of optimized breeding schemes • Development of molecular marker sets for selection and quality control • Elite x elite crosses in each breeding pipeline • Selection of candidate varieties for registration and release • Implementing digital data collection from genotyping and phenotyping trials • Training workshops on data analysis, data management, statistical designs	• At least 3 key traits that drive variety adoption defined in each market segment • Marker sets available for low- and mid-density applications • Breeding populations addressing the key traits in each market segment • Candidate varieties in field testing from each breeding pipeline • 100% of field trials run use modern field designs and follow standard operating procedures (SOP) • African potato-breeding network operating in 3 East African countries	• Breeders have improved understanding on the importance of data-driven decision-making • Better data quality from the trials • Each breeding pipeline routinely monitors GG	• GG increased annually by at least 1% for key traits in both crops • Modernized breeding practices in use by CIP and NARS • A targeted and measurable product replacement strategy • A market-driven product delivery system	• Increased potato and SP variety adoption by smallholders • Vulnerable populations have better access to nutritious and resilient potato and SP varieties

IMPACT	Improved livelihoods and health of smallholder potato and sweetpotato farmers in Africa, Asia, and Latin America.

V. RESEARCH PROJECT REPORT

a. OBJECTIVE 1: TARGETED AND MEASURABLE PRODUCT REPLACEMENT STRATEGY

i) Description: Demand-driven approaches to product targeting, development, and management will strengthen the ability of our breeding networks to deliver valuable products for farmers and stakeholders. However, our success also relies on capacity building to increase the ability of national systems to effectively collaborate on market knowledge, variety development, seed release, and out-scaling.

ii) Location: Bangladesh, Ethiopia, Kenya, and Peru

iii) Collaborators: BARI, BAU, EIAR, Kenya Agricultural and Livestock Research Organization, Pataz, Yanapai, and EiB

iv) Achievements: The key components toward reaching this objective are (1) continuously improved product profiles; effective, optimized breeding pipelines generating GG for the important traits; and efficient breeding networks with NARS. The product profiles are an evolving concept and need feedback, particularly from end-users. One such detailed study was undertaken for SP, focusing on trait prioritization and valuation analysis to capture socio-demographic and trait preference from supply chain actors and by gender. Such results are valuable for the breeding program as they allow the selection of the key traits for the product profiles in the different market segments and may in the future secure the adoption of the new varieties. The USAID investment contributes to six breeding pipelines targeting 3.8 million ha of potato and 4.3 million ha of SP cultivation areas, respectively. Each of the pipelines continued the normal breeding processes generating progenies, following the early- and late-testing schemes as well as field testing to select candidate varieties for variety release with NARS. Toward improving the breeding networks with NARS for potato in Africa, the NARS facilities at the University of Nairobi–Kabete Campus (University of Nairobi) and the Kenya Plant Health Inspectorate Service Plant Quarantine Station were upgraded with new net houses and storage for chemicals and fertilizers.

v) Capacity Building: To optimize the breeding pipelines, the breeding teams have engaged with EiB for breeding scheme optimization, where improvement plans were identified for both crops. The teams are committed to implementing these plans.

vi) Lessons Learned: The first-generation product profiles developed so far still need to be improved to achieve more granularity. The consultation from the value chain actors and end-users proved to be a success, and such an approach needs to be repeated in other market segments. Breeding pipelines still need to be evaluated for the size of the investment, and calculation of GG must become a natural process in every pipeline.

vii) Presentations and Publications

Mudege, N.N., Mayanja, S., Nyaga, J., Nakitto, M., Tinyiro, S.E., Magala, D.B., Achora, J.C., Kisakye, S., Bamwirire, D., Mendes, T., and Muzhingi, T. 2020. Prioritizing quality traits for gender-responsive breeding for boiled potato in Uganda. *International Journal of Food Science & Technology*.

b. OBJECTIVE 2: STREAMLINED BREEDING OPERATIONS

i) Description: Streamlined breeding operations include high throughput genotyping and phenotyping and a breeding decision and informatics support system to assess reliable performance of clones and to provide feedback for the development of data-driven product profiles. Efficient data management systems are critically required to keep track of clone performance information, pedigree, and DNAbased data generated throughout the breeding process. Furthermore, high-quality curated data are needed to enable measurement of breeding programs and to keep track of performance, pedigree, geographical, and DNA- and image-based data.

ii) Location: Uganda, Peru, and Kenya

iii) Collaborators: EiB, Boyce Thompson Institute (BTI), and Wageningen University and Research (WUR)

iv) Achievements: With the support of EiB, the program has focused on the breeders' equation and increasing the GG in various ways. All new crosses made during 2020 were elite x elite crosses and focused on the product profiles. Notably in SP these included high Fe elite x elite crosses. Through EiB support the breeding teams of both crops have participated in the breeding scheme optimization sessions, focusing on simulating the optimal program size for SP and use of selection indices in potato. Potato breeding has made significant advances in incorporating trait associated markers in the breeding pipeline, as a low-density single-nucleotide polymorphism (SNP) panel that was developed in 2017 was augmented with additional markers from the global potato-breeding community. Similarly, both crops developed a quality control SNP marker assay for identity verification. Potato is moving ahead with genomic selection to shorten the breeding cycle. To this end, the training population comprising 500 potato clones was planted in two locations in Peru for phenotypic evaluation. A mid-density molecular marker set was developed and tested for potato genomic selection with EiB support. In addition, CIP has significantly strengthened its biometric capabilities, and the use of linear mixed models and advanced designs (p-reps, augmented, row-column designs) has become routine in all breeding pipelines. The breeding program optimization aims at achieving a faster rate of GG and development of potato and SP varieties for the poorest smallholder farmers in the world. By focusing on traits such as Fe content and quality traits, our breeding program responds specifically to the need of women, contributing to gender equality. To harmonize the data management of all breeding activities carried out by CIP, a contract was signed with BTI to host PotatoBase, which belongs to the database structure BreedBase. The decision to harmonize the data management system between potato and SP was taken to minimize costs and to increase the efficiency with respect to development, training, and maintenance for data recording, management, and analysis. Furthermore, all analytical or other tools available in SweetpotatoBase will also be automatically available in PotatoBase.

v) Capacity Building: CIP is committed to operational excellence in breeding data management, as this is an important part of the breeding program modernization. The team has developed SOP for breeding data management and organized capacity-building events (see Section VI). Training in the use of mixed models and statistics support in experimental design and data analysis provided to the breeders, "Phenotypic modelling across the target population of environments" was organized with expert teachers from WUR.

vi) Lessons Learned: Systematically measuring the GG in the breeding program is a key metrics to evaluate the success of each pipeline, and it needs to become a performance indicator.

vii) Presentations and Publications

Amoros, W., Salas, E., Hualla, V., Burgos, G., De Boeck, B., Eyzaguirre, R., zum Felde, T., and Bonierbale, M. 2020. Heritability and genetic gains for iron and zinc concentration in diploid potato. *Crop Science* 60(4):1884–1896. https://doi.org/10.1002/csc2.20170

Bararyenya, A., Olukolu, B.A., Tukamuhabwa, P., Grüneberg, W.J., Ekaya, W., Low, J., Ochwo-Ssemakula, M., Odong, T.L., Talwana, H., et al. 2020. Genome-wide association study identified candidate genes controlling continuous storage root formation and bulking in hexaploid sweetpotato. *BMC Plant Biology* 20(1) DOI: 10.1186/s12870-019-2217-9

Bararyenya, A., Tukamuhabwa, P., Gibson, P., Grüneberg, W.J., Ssali, R., Low J, Odong, T., Talwana, H., Mwila, N., and Mwanga, R. 2020. Continuous Storage Root Formation and Bulking in Sweetpotato. *Gates Open Res* 3:83.

Drapal, M., Lindqvist-Kreuze, H., Mihovilovich, E., Aponte, M., Bonierbale, M., and Fraser, P.D. 2020. Cooking dependent loss of metabolites in potato breeding lines and their wild and landrace relatives. *Journal of Food Composition and Analysis* 88: 103432.

Gemenet, D.C., Kitavi, M., David, M., Ndege, D., Ssali, R.T., Swanckaert, J., Makunde, G., Yencho, Grüneberg, W.J., et al. 2020. Development of diagnostic SNP markers for quality assurance and control in sweetpotato [*Ipomoea batatas* (L.) Lam.] breeding programs. *PLoS ONE* 15(4) DOI: 10.1371/journal.pone.0232173

Jongstra, R., Mwangi, M., Burgos, G., Zeder, C., Low, J., Mzembe, G., Lina, R., Penny, M., Andrade, M., Fairweather-Tait, S., and Felde, T. 2020. Iron absorption from iron-biofortified sweetpotato is higher than regular sweetpotato in Malawian women while iron absorption from regular and iron-biofortified potato is high in Peruvian women. *Journal of Nutrition*150(12):3094–3102.

Low, J.W., Ortiz, R., Vandamme, E., Andrade, M., Biazin, B., and Grüneberg, W.J. 2020. Nutrient-dense orange-fleshed sweetpotato: advances in drought-tolerance breeding and understanding of management practices for sustainable next-generation cropping systems in sub-Saharan Africa. *Front. Sustain. Food Syst.* 4:50 DOI: 10.3389/fsufs.2020.00050

Toubiana, D., Cabrera, R., Salas, E., Maccera, C., Franco dos Santos, G., Cevallos, D., Lindqvist-Kreuze, H., Lopez, J.M., and Maruenda, H. 2020. Morphological and metabolic profiling of a tropical-adapted potato association panel subjected to water recovery treatment reveals new insights into plant vigor. *The Plant Journal* 103(6):2193–2210.

Zhou, C., Olukolu, B., Gemenet, D.C., Wu, S., Grüneberg, W., Cao, M.D., Fei, Z., Zeng, Z.B., George, A.W., Khan, A., and Yencho, G.C. 2020. Assembly of whole-chromosome pseudomolecules for polyploid plant genomes using outbred mapping populations. *Nature Genetics* 52(11):1256–1264.

Zúñiga, N., Gastelo, M., Bastos, C., Reyes, J., Alania, E., and Ninalaya, E. 2020. Obtaining New Potato Cultivars with Late Blight Resistance and Adapted to Climate Change Using Participatory Varietal Selection. *Journal of Agricultural Science and Technology* B10:17–27 DOI:10.17265/2161-6264/2020.01.003

VI. HUMAN AND INSTITUTIONAL CAPACITY DEVELOPMENT

a. SHORT-TERM TRAINING

COUNTRY OF TRAINING*	BRIEF PURPOSE OF TRAINING	WHO WAS TRAINED	NUMBER TRAINED		
			M	F	Total
	Data management: introduction to SweetpotatoBase	CIP and NARS researchers	15	6	21
	Data management: digital tools for phenotyping	CIP and NARS researchers	12	6	18
	Data management: digital tools for crossing experiments	CIP and NARS researchers			
	Data management: R training	CIP and NARS researchers			
	Statistics analysis of agricultural data: “Phenotypic modelling across the target population of environments”	CGIAR and NARS researchers	20	10	30

*All training was done online due to COVID-19 restrictions; hence all “countries” where training was delivered are global.

b. LONG-TERM TRAINING

TRAINEE NUMBER	SEX	UNIVERSITY	DEGREE	MAJOR	PROGRAM END DATE	DEGREE GRANTED (Y/N)	HOME COUNTRY
1	F	Michigan State University	PhD	Plant breeding, genetics, and biotechnology	February 2020	Y	Kenya
2	F	Egerton University	PhD	Plant biotechnology	September 2021		Kenya
3	F	Universidad Nacional Del Altiplano Puno (UNAP)	BSc	Agronomy	December 2022		Peru
4	F	UNAP	BSc	Agronomy	December 2022		Peru
5	M	University of Nairobi	MSc	Plant breeding and biotechnology	March 2021		Kenya
6	M	Egerton University	PhD	Crop protection	August 2022		Kenya
7	M	UNAP	BSc	Agronomy	December 2022		Peru
8	M	UNAP	BSc	Agronomy	December 2022		Peru

c. INSTITUTIONAL DEVELOPMENT

i) Description: CIP has excelled at rapidly upgrading breeding data management for better data quality and biometrics to adopt modern experimental designs and linear mixed models with appropriate variance/ covariance structures. This has been achieved by investments in training and staff, through RTB, GIZ, and USAID funding, and through the continuous support of EiB. EiB breeding scheme optimization support has allowed CIP to optimize the number of parents used, along with tester selection in the mid- and long-term, based on simulations. It has also enabled CIP to predict the long-term GG that will be achieved by different breeding approaches. This support has enabled changes that lower the uncertainty and risks involved in major innovations such as hybrid breeding.

EiB training has also been incorporated into CIP product profiles to ensure that customer-preferred traits—including gender, biofortification, and particularly quality traits driving adoption—are embedded in the breeding process. Furthermore, CIP was selected to pilot new approaches to customer trait determination alongside AbacusBio in Uganda. Through this engagement, EiB has supported CIP in our commitment to become a customer-driven breeding organization that prioritizes the traits that are most important to end-users.

ii) Partners: EiB, WUR, and BTI

VII. INNOVATION TRANSFER AND SCALING PARTNERSHIPS

a) Plan of action:

i) Steps taken: New partnerships were formed in Peru to continue the field testing of advanced biofortified potato clones from CIP's breeding program toward variety release. In Ethiopia the national program continued field testing of advanced potato clones, and the Bangladesh national program was evaluating early- and late-stage SP breeding germplasm.

ii) Partnerships made: *Ethiopia*: EIAR; *Peru*: INIA–Puno and NGOs Fovida and Asociación Pataz; *Bangladesh*: BARI and BAU

iii) Technologies ready to scale: NA

iv) Technologies transferred: NA

v) Technologies scaled: NA

VIII. ENVIRONMENTAL MANAGEMENT AND MITIGATION PLAN

Regarding the mitigation and monitoring activities as per the Environmental Management and Mitigation Plan, appropriate pesticide use protocols to safeguard the health of personnel and to protect local ecosystems were implemented in the field and greenhouse trials. In CIP-led trials, only trained personnel are permitted to apply pesticides, and the said chemicals are stored and disposed following specific guidelines. Owing to COVID-19 emergency health measures and social distancing, regular hand-washing and the use of personal protective equipment were practiced in the laboratory, greenhouse, and field.

IX. OPEN-DATA MANAGEMENT PLAN

CIP has an open-access and open data implementation plan that was developed pursuant to the CGIAR Open Access and Data Management Implementation Guidelines. CIP has created its own Publications Policy, Open Data and Data Management Policy, and Open Data and Data Management Guidelines and Procedures supporting processes and workflows linking to our framework project life cycle. Publications cycle and data management cycle feed into the post-award section of any project at CIP. These two cycles will guide all processes related to open data at CIP. Dataverse is a commonly used open-source data repository platform that facilitates the ability to publish, share, reference, extract, and analyze research data. It helps to make research data openly accessible. Each Dataverse contains studies or collections of studies, and each study contains metadata that describes the data plus the actual data and complementary files. CIP Dataverse can be accessed at https://data.cipotato.org/. All project data have been deposited in this repository.

X. PROJECT MANAGEMENT ACTIVITY

Regular meetings were undertaken with the project management unit to keep track of the budget spending and the activities. The annual project meeting was organized on 15–17 December 2020 to review and discuss the status of key activities.

XI. OTHER TOPICS

To improve the gender responsiveness of the potato and SP product profiles, the breeding staff participated in an activity organized by the RTB gender team to analyze the current product profile templates created by EiB and how to make those more gender responsive. In Peru, the biofortified candidate potato varieties were field tested, with smallholder farmers using the PVS methodology.

XII. ISSUES AND HOW THEY ARE BEING ADDRESSED

The COVID-19 health emergency impeded travel and staff movement. Contingency plans were developed during the second quarter of 2020 as a response to the COVID-related lockdowns and other restrictions to mitigate the impact on project activities. In Peru changes were made in the partner responsibilities and contracts to enable continuation of field trials, even though CIP staff was unable to travel to perform normal monitoring activities. In Kenya field trials were delayed, and the activities focused on seed maintenance. Strict health and safety protocols were established to enable laboratory activities to continue in Peru.

XIII. FUTURE DIRECTIONS

According to the World Health Organization, nearly 25% of the world's population suffers from Fe deficiency or anemia. The situation is particularly severe in SSA, where prevalence of anemia among preschool-aged children has been reported to range between 37.6% and 76.1%, depending on the country (HarvestPlus). India and Bangladesh also have high prevalence of early childhood anemia, respectively at 46% and 69.4%. Our recent investigation showing that potato has an exceptionally high bioavailability of Fe means that the crop has a great opportunity to make a real difference in places such as Bangladesh, India, and Rwanda, where per-capita consumption of potato annually is relatively high. According to the Food and Agriculture Organization of the United Nations, in 2017 the per capita consumption in these countries was 49.9 kg, 25.5 kg, and 93.4 kg, respectively. The average daily need of absorbable Fe in children is 0.64 mg, and in women 1.42 mg. Assuming 24.8% absorption and the daily need of 1.42 mg, 200 g of the best-performing clone BIOT-637.118 from our Fe-biofortified potato population can cover 28.8% of the daily need. This is very close to the 30% threshold level required from a biofortified crop. With this information at hand, we can determine the breeding target for Fe content in potato and start setting up the breeding network for new products from the biofortified potato breeding pipeline.

In 2021 we will continue to engage with the PPP and collaborate with the Syngenta-funded project with the aim of dissemination and accelerated adoption of public-private bred varieties from the TAP-5 (CIP x HZPC) tropical breeding pipeline.

APPENDIX: THREE SUCCESS STORIES

BIOAVAILABILITY OF IRON IN POTATO

In developing countries, about half of pregnant women and 40% of preschool children suffer anemia, which affects about 2 billion people globally. Moreover, anemia impairs children's physical and mental development, makes adults less productive, and contributes to about 20% of maternal deaths.

A potato iron-absorption study for humans was conducted by CIP in collaboration with ETH Zürich and Peru's Nutritional Research Institute. The study reveals that potato could play an important role in efforts to reduce iron deficiency, the leading cause of anemia.

The study focused on iron-deficient women from Peru's Huancavelica region who ate 500 grams of potatoes each day for two weeks. It found that the rate of iron absorption from yellow-fleshed potatoes was much higher than that reported for other crops. Whereas people absorb only about 2–10% of the iron in most vegetables, 8% of the iron in pearl millet and less than 10% of the iron in beans, participants in this study absorbed 28% of the iron in the yellow-fleshed potato they ate.

PHOTO: SARA FARJADO (CIP).

Photo 1. Smallholder woman from Huancavelica with her baby and a basket of native potatoes from her farm.

Participants in the Huancavelica study ate 500 grams per day of a high-iron, purple-fleshed potato or a popular, yellow-fleshed native potato called 'Peruanita'. Though the purple-fleshed potato had double the iron concentration of 'Peruanita', the iron absorption (13%) was found to be lower. Since phenolics may inhibit iron absorption, the lower iron absorption from the high-iron purple-fleshed potato meal may be explained by its higher phenolic content (528 mg/ 500 g) compared with the yellow-fleshed variety (148 mg/100 g). However, we need a study to evaluate and determine which phenolic has the main role on inhibiting iron absorption in potatoes.

The 500 grams of the yellow-fleshed potato that participants consumed provided around 33% of the daily iron requirement of a woman of reproductive age. It is expected that a high-iron (biofortified) yellow-fleshed potato will have a higher iron absorption and, consequently, contribute with more than 50% of her daily iron requirement. A study to confirm that hypothesis is planned for 2021.

More detailed information can be found in the manuscript https://pubmed.ncbi.nlm.nih.gov/33188398/

MODERNIZATION OF THE CIP BREEDING PROGRAM

CIP's breeding programs aim to release new potato and sweetpotato varieties that are high yielding, nutritious, and meet targeted market preferences, and to have these varieties grown on farmer's fields. To achieve this goal, genetic gains of the relevant traits must be realized as fast as possible and outperform the varieties currently dominating the targeted market. In recent years, breeding has become a versatile team effort. This also means that there are many different breeding components that can be targeted for improvement, eventually leading to higher genetic gains. A modernization effort of CIP's breeding programs was set up, with the aim to continuously improve the efficiency of breeding programs. The programs included the adoption of more adequate field designs and new statistical methodologies, the optimization of breeding schemes, and the pursuit of operational excellence in breeding data management.

To increase operational excellence, standard operating procedures for breeding data management were developed for sweetpotato and compiled in a document (https://cgspace.cgiar.org/handle/10568/109605). These procedures were established in the framework of the SweetGAINS project, and their implementation was later extended to all CIP sweetpotato-breeding programs. Compliance with the procedures ensures the use of naming conventions, general data curation rules, measurement protocols, official trait ontology, and fixed data workflows (for phenotyping, crossing experiments, laboratory analyses, germplasm inventory, and genotyping project management) based on digital data recording tools and the relational database SweetpotatoBase (https://sweetpotatobase.org/). Guidelines about the use of modern statistical experimental designs for field experiments, depending on the breeding stage, are also included in the document. The transition of full compliance to the standard operating procedures began in 2020 and should be completed in 2021 for all CIP's sweetpotato-breeding programs. A similar initiative was taken for the potato-breeding programs, but these procedures are still under development. All these efforts are made to increase the quality of a very valuable good in a breeding program, namely the data on which breeding decisions are finally based.

PHOTO: MICHAEL MAJOR (CROP TRUST).

Photo 2. A technician records flowering scores of potato-breeding lines using Fieldbook application on a smartphone.

Obtaining high-quality data is a first important step, but afterwards appropriate statistical inference on that data is also crucial. The transition from classical statistical methodologies to analyses based on linear mixed models has been made in CIP's breeding programs. This leads to more realistic predictions of genotype performances and therefore eventually to higher genetic gains since better informed decisions can be taken.

Finally, under the Excellence in Breeding initiative, CIP potato- and sweetpotato-breeding programs have started optimization exercises. These exercises aim to improve the breeding pipelines, not only in terms of the breeding scheme used but also in how decisions are taken. For a sweetpotato-breeding pipeline, the optimal breeding program size was simulated. For a potato-breeding pipeline, the use of a selection index for multi-trait selection was assessed. Both optimization exercises are leading to concrete changes in the respective breeding pipelines.

EXPLOITING HETEROSIS FOR MAJOR GAINS IN CLONAL CROPS: HOW SWEETPOTATO HYBRIDS WENT FROM PIPE DREAM TO REALITY

Orange-fleshed sweetpotato is one of the most important examples of breeding impact in CGIAR history, with over 6 million smallholder farmers and their families now benefiting from the vitamin A biofortified crop. To reach a new level of impact, CIP breeders set out to realize the theoretical potential of hybrid sweetpotato breeding to achieve a step-change in genetic gains for root yield and climate resilience-related traits within a breeding cycle of 5–6 years.

Sweetpotato is a complex autopolyploid and highly heterozygous clonal species. For decades its high rate of heterozygosity, or genetic variance, was thought to realize large gains by exploiting the "hybrid vigor" effect (heterosis). Quantitative traits like yield or abiotic stress resilience may even be largely determined by heterosis. Breeding schemes that exploit heterosis are rarely explored in clonal crops due to the difficulty of estimating the gains being achieved, and are often dismissed as a questionable investment.

In 2010 CIP breeders began to develop two divergent populations in Peru and at African regional platforms, each offering contrasting traits relevant to the same product profile. After a reciprocal recurrent breeding selection cycle, three hybrid populations were obtained for orange-fleshed sweetpotato: wide adaptation and earliness; no or low sweet taste after cooking (demanded by small-scale and industrial food processing); and double stacked with vitamin A and high-iron traits.

Initial field results confirmed that hybrid breeding can potentially revolutionize sweetpotato breeding, along with other clonal crops. The three populations showed gains of 81.5–132.4% in storage root yield; offspring clones of the three populations frequently outperform checks. Multiple trials have shown that hybrid breeding can surpass the gains of 36 years of traditional breeding within just 5–6 years. Hybrid sweetpotato breeding offers similar results to hybrid maize, which has maintained a consistently high rate of genetic gain since being introduced in the 1930s, dominating the global maize market and offering a clear advantage to smallholder farmers who can adopt it.

To deliver sweetpotato hybrid cultivars to smallholders in Africa, CIP has moved to scale out this innovation through our regional breeding hubs. Each of these hubs supports the region by disseminating true seed and selecting new advanced clones. By distributing hybrid seed to national agriculture research systems in the region, the chances of finding good clones increase immensely. Hybrid breeding started in the Mozambique and Uganda regional hubs for the 2019/2020 season. CIP's national partners are expected to lead the registration of the first commercial sweetpotato hybrid clones as early as 2022.

The hybrid sweetpotato innovation proves that heterosis can be successfully exploited to achieve a step-change in the rate of improvement of root, tuber, and banana clonal crops. These offer highly nutritious and biofortified dietary options that can be grown in a diverse range of environments, even under climate change. Because of its short crop cycle, as well as the insights and failures gathered from this experience, sweetpotato could become a model clonal crop whereby heterosis-related hypotheses could be tested before their implementation in other clonal crops.

Photo 3. Hybrid sweetpotato genotype flanked by its progenitors. (PHOTO: FEDERICO DIAZ)