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# More fruit for food security: Selecting climate-smart bananas for the different agro-ecozones and markets in the African Great Lakes region.

Jan 2021 – Dec 2021



Field trial in Mbarara, Uganda, mulched with swamp grass to reduce weeds and soil moisture loss. Photo credit: Bioversity International/L. Machida

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“This project prolongation will **(i)** **disseminate** the results and continue the **capacity building**, **ii)** continuethe **high throughput phenotyping** in the Bananatainer, coupled to the **molecular and** **genetic analysis,** **(iii)** **start the validation** of **21 selected varieties** **under field conditions**, and **(iv)** conduct **key informant interviews** with stakeholders regarding **variety choice & climate change**, and assess the possibility to **increase the digital inclusion** for farmers.”

# Introduction

Bananas (*Musa spp.*) are an important staple crop for millions of inhabitants of the East African Great Lakes region with the highest per capita consumption in Uganda (Karamura et al., 1998). However, the production of the East African highland cooking bananas (EAHB) which are endemic to the region is threatened by a myriad of challenges. Whilst commendable achievements have been made in reducing the impact of the biotic stresses by releasing alternative or improved cultivars, it is anticipated that the adverse effects of climate change will further threaten crop production leading to erratic crop harvests (IPCC 2007). It is predicted that 30% of the African banana growing areas will be negatively affected (Rippke et al., 2016). The genetic characterization and evaluation of suitability of gene bank accessions for targeted agro-ecological regions and markets have contributed to increased food, feed, fiber, and fuel demands (McCouch et al., 2013). An example for banana is the Kagera region in Tanzania where the introduction of clean material and disease resistant cultivars from the ITC has contributed to agronomic improvements in farmers’ fields (Gallez et al., 2004). This project was funded by the Belgian Technical cooperation. The typical smallholder and rain-fed banana production systems should benefit from sustainable production intensification to reduce the current yield gaps. This includes the use of germplasm that is perfectly suitable for the local agro-environment. Farmers have already started to introduce diversity on their farms based on (local) expertise and tradition (Kamira et al., 2016; Ocimati et al., 2014; Turner et al., 2016). **The overarching goal of this project is to identify a set of “climate-smart” banana accessions that is culturally accepted and can contribute to close the yield gap in the African Great Lakes region**.

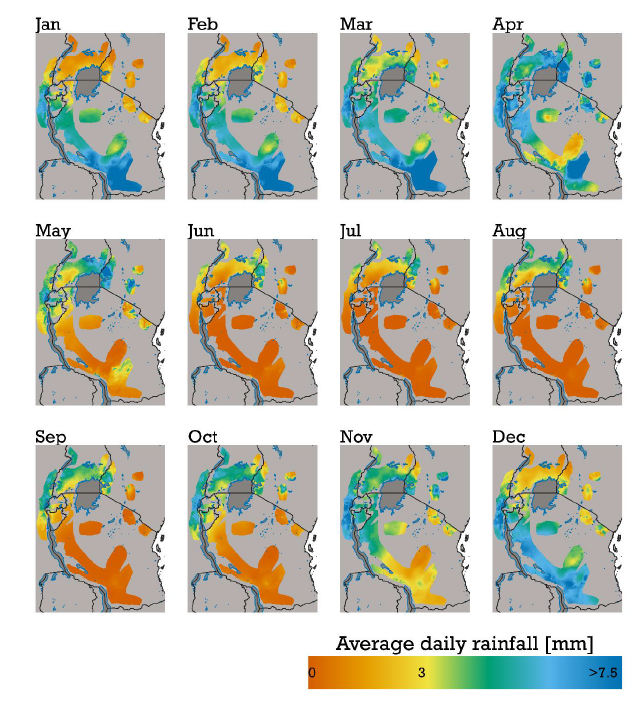
# Results from previous work

## Scientific output

With the support from the Belgian government and other donors, KU Leuven and Bioversity International have built up a unique and world recognized expertise in the use of banana diversity for small-scale farming over the last 30 years. We have collected and managed the world banana heritage at the International Transit Centre (ITC) to secure long-term conservation for future generations (Van den houwe et al., 1995, 2003). The ITC gene bank collection of banana houses more than 1600 accessions, including cultivated varieties, improved hybrids and wild relatives. However, although a major part of the managed germplasm is genetically characterized (Christelova et al., 2017), a large fraction has not been evaluated for agronomic traits. As long as gene banks are not fully characterized, phenotyped, and accessible on a web platform such as the MGIS (Ruas et al., 2017), it is difficult to identify what is missing in the germplasm collections. In the past DGD projects, we have explored the diversity of our valuable collection by developing a phenotyping facility to study water-related stress in banana under controlled environmental conditions (Carpentier, 2011; Carpentier et al., 2015; Kissel et al., 2015; Vanhove et al., 2012a; Zorrilla et al., 2016). Subsequently, we have applied this strategy to the Taxonomic Reference Collection[[1]](#footnote-1) (32 representatives of the global Musa biodiversity (29 cultivars and 3 wild relatives)). Of the eight varieties that showed the best growth potential under limited water conditions, five had an ABB genome constitution (van Wesemael et al., 2019). Those ABB varieties had a lower maximal transpiration rate, kept this maximal transpiration for a shorter time, and consumed less water per day (van Wesemael et al., 2019). To explore the genetic diversity and identify the **unique genes** of those ABB varieties, an in-depth study was performed which confirmed that unique chromosome structures exist containing unique genes that divide the ABB subgroup in 9 different subdivisions (Cenci et al., 2020). We have additionally confirmed that those specific chromosome structures and unique genes have also an impact on plant traits that contribute to drought tolerance (Cenci et al., 2019; van Wesemael et al., 2018; van Wesemael et al., 2019). All unique genes have been made publicly available on our gene bank web portal[[2]](#footnote-2). A reference genome for the ABB group is also being finalized (Rouard et al, in prep) and will support a broad range of genomics studies to better characterize the genetic studies of cultivated bananas.

However, local markets have specific demands and farmers often prefer traditional cultivars because of their superior consumption qualities, even if new/other cultivars display superior agronomic traits and better performance under stress conditions. In order to promote and facilitate the use of cultivars with improved characteristics, a **deeper understanding of the local diversity and its potential to withstand current and future climate challenges** is required. Therefore, during the ongoing research project, (i) we have focused on understanding local quality preferences (Marimo et al., 2020), and (ii) we designed a high throughput sophisticated controlled lab environment (the so-called Bananatainer) where we simulated the different climate zones of the African Highlands (Figure 1, 2 and 3).

**Figure 1:** Average day temperature in the banana growing areas of the Great Lakes region during the wet season March-April. Five different areas have been studied in detail and are highlighted: Luwero, Mbarara, Bukoba, Rungwe and Moshi.





**Figure 3:** Bananatainer: This controlled growing environment grows 504 plants simultaneously for 6 weeks up to 70 cm height.

**Figure 2:** Average daily rainfall per month in the Great Lakes region height.

Our research pipeline allows us to (i) select from the International Transit Centre the relevant subsets, (ii) understand in a high throughput manner the potential and the weaknesses of the currently used diversity and identify varieties with improved traits, (iii) save time and money by developing a more targeted approach that reduces the costs associated with extensive field trials, and (iv) develop a demand-driven introduction of climate-smart varieties in specific areas for direct use by farmers or as parents in breeding programs.

Crop evaluation is critical for variety release, “seed” marketing and distribution as well as variety recommendations for farmers (Brown et al., 2020). So far during the 2017-2020 phase of the project, we studied the *on*-*farm* diversity of 5 different agro-ecological zones across Uganda and Tanzania[[3]](#footnote-3) (Figure 1, Table 1). We evaluated a strategic subset of the collection (**105 varieties** of which 41 East African Highland varieties) **in the Bananatainer** for their compatibility under the aforementioned ecozone conditions. Our study indicates that the average optimal mean growth temperature for our subset of varieties was 26.8°C. Importantly, our modelling identified **21 varieties with an optimal growth at less than 25°C** (Figure 4).



**°C**

**Figure 4:** Distribution of the calculated optimal mean temperatures for the analyzed varieties in the Bananatainer. The average optimal mean temperature is 26.8°C.

Three representatives (one dessert banana of the Cavendish subgroup (Williams), one East African Highland banana (Mbwazirume), and one ABB Bluggoe (Cachaco)) have been studied in the field at 5 different locations (Figure 1) to measure the effect of the specific agro-ecozone conditions (Table 2) on the crop cycle. These field experiments complemented the extensive work on these 3 varieties in our labs for the past 10 years (Carpentier et al., 2007; Carpentier et al., 2010; Carpentier et al., 2011; Cenci et al., 2019; Cenci et al., 2020; Henry et al., 2011; Kissel and Carpentier, 2016; Kissel et al., 2015; Samyn et al., 2007; van Wesemael et al., 2018; van Wesemael et al., 2019; Vanhove et al., 2012a; Vanhove et al., 2012b; Vanhove et al., 2015; Zorrilla et al., 2016).

Table 1: List of the local diversity in Tanzania and Uganda.

|  |  |  |  |
| --- | --- | --- | --- |
| **Region** | **Genomic constitution** | **Subgroup** | **Evaluated in Bananatainer** |
| **Bukoba** | **AA** | Mchare | Yes |
|  | **AAA** | Cavendish | yes |
|  |  | EAHB | yes |
|  |  | Gros Michel | yes |
|  |  | Ibota | yes |
|  | **AAAA** | FHIA hybrid | yes |
|  | **AAAB** | FHIA hybrid | no |
|  | **AAB** | Kamaramasenge | yes |
|  |  | Plantain | yes |
|  |  | Pome | yes |
|  | **AABB** | FHIA hybrid | no |
|  | **ABB** | Bluggoe | yes |
|  |  | Pisang Awak | yes |
|  |  | Saba | no |
| **Luwero** | **AAA** | EAHB | yes |
|  |  | Gros Michel | yes |
|  |  | Ibota | yes |
|  | **AAAA** | FHIA hybrid | yes |
|  | **AAB** | Kamaramasenge | yes |
|  |  | Plantain | yes |
|  | **AB** | Ney Poovan | no |
|  | **ABB** | Bluggoe | yes |
|  |  | Pisang Awak | yes |
|  |  |  |  |
| **Mbarara** | **AAA** | EAHB | yes |
|  |  | Gros Michel | yes |
|  |  | Ibota | yes |
|  |  | Red | yes |
|  | **AAB** | Kamaramasenge | yes |
|  | **ABB** | Bluggoe | yes |
| **Meru** | **AA** | Mchare | yes |
|  | **AAA** | Cavendish | yes |
|  |  | EAHB | yes |
|  |  | Gros Michel | yes |
|  |  | Ilalyi | no |
|  | **AAB** | Kamaramasenge | yes |
|  |  | Plantain | yes |
|  |  | Pome | yes |
|  | **ABB** | Bluggoe | yes |
|  |  | Pisang Awak | yes |
| **Moshi** | **AA** | Mchare | yes |
|  | **AAA** | Cavendish | yes |
|  |  | EAHB | yes |
|  |  | Ilalyi | no |
|  | **AAB** | Kamaramasenge | yes |
|  |  | Plantain | yes |
|  |  | Pome | yes |
|  | **ABB** | Bluggoe | yes |
|  |  | Pisang Awak | yes |
| **Rungwe** | **AAA** | Cavendish | yes |
|  |  | Red | yes |
|  | **AAB** | Plantain | yes |
|  |  | Pome | yes |
|  | **ABB** | Bluggoe | yes |
|  |  | Pisang Awak | yes |

Table 2: Weather information on the 5 sites

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Tanzania | | | Uganda | |
| **Moshi** | **Rungwe** | **Bukoba** | **Luwero** | **Mbarara** |
| Annual mean temperature (°c) | 19.6 | 20.7 | 21.2 | 21.5 | 20.9 |
| Annual average Growing Degree Days (GDD) | 2020 | 2459 | 2615 | 2727 | 2529 |
| Average annual total precipitation (mm) | 1546 | 1050 | 917 | 1064 | 1132 |
| Season | Bimodal  (dry Jan-Feb and Aug-Oct) | Unimodal  (dry May-October) | Unimodal  (dry June-September) | Bimodal  (dry Jan-Feb and Jul-Aug) | Bimodal  (dry Jan-Feb and Jun-Aug). |

In practice, the long-rate of development of banana plants is influenced by temperature (Turner, 1990) while the short-term growth is more a function of water supply. While water shortage could in theory be solved easily, in practice irrigation is hardly available in the Great Lakes region. Machovina and Feeley (2013) modelled the optimal annual mean temperature for commercial banana culture at 26.2°C (Machovina and Feeley, 2013). Our Bananatainer analysis revealed a similar range temperature (26.8°C) for the tested cultivars. However, the average temperatures in the African highland zones are far below the optimal annual mean temperature (Figure 1, Table 2). A lower temperature prolongs the crop cycle and reduces the annual production. In Luwero and Bukoba, where the annual mean temperature is the highest of the 5 sites, we observed the shortest crop cycle (Figure 6). Obviously, the suboptimal temperature ranges cannot be controlled by any farm management.

The effect of temperature can be normalized to a certain extent by the use of thermal time. Thermal time is often expressed as growing degree days (GDD). Depending on the variety and on other environmental limiting factors (water deficit, photoperiod, soil fertility, etc.), bananas need between 2400 and 4000 growing degree days to complete their cycle (Mboula, 2014; Turner and Fortescue, 2010; Turner et al., 2016; Turner et al., 2009). The Ugandan and Tanzanian sites show a thermal time near the described maximum of 4000 GDD and Rungwe even has a thermal crop cycle time of more than 5000 GDD (Figure 7). This illustrates that the African highland zone is challenging for banana growth and points towards an additional stress factor on top of the suboptimal growing temperature. Indeed Rungwe has the longest dry season (Figure 2, Table 2).

We showed that there is also a significant interaction between the region and the variety, meaning that some varieties grow better in some regions (Figure 8). In Luwero and Bukoba, the two warmest regions, the East African highland banana Mbwazirume had the highest yield per time unit while in Moshi the Cavendish dessert type, Williams, clearly outperformed the other two varieties. The region of Moshi has excellent fertile volcanic soils which boost high yielding varieties like the Cavendish ones. This resulted in a spectacular increase in yield for Williams (factor 4.3 compared to the lowest yielding region) while the increase was much more moderate in the other varieties: Mbwazirume and Cachaco (Figure 8).

Another important result is that, the Cachaco ABB variety of which we predicted to have a lower maximal transpiration and water consumption per day in the field (van Wesemael et al., 2019), exhibited a slow but stable yield even under severe stress conditions like in Rungwe. This result reinforced the usefulness of our evaluation pipeline and modeling work.

Finally, Mbwazirume, a local variety, which shows an overall good yield, was the preferred variety concerning quality characteristics in Luwero, Moshi, Bukoba (Madalla et al in preparation) but it is quite sensitive to environmental stress, resulting in a steep drop in yield (Figure 8).

The selection of banana varieties to grow in the local fields is often gender specific. Statistical differences in the importance of banana traits between men and women banana farmers were found for cooking quality (taste, color, softness), beer quality, and resistance to Fusarium wilt (Marimo et al. 2020). Differences were attributed to underlying preferences based on gender roles; men/beer production and women/cooking, respectively. This emphasizes the need to investigate multiple factors not only limited to environmental stress behavior but also gender and consumer preferences, to develop climate smart bananas that are adapted to specific environments and have user- and consumer-preferred characteristics.

**Figure 6**: Average crop cycle in days of the 3 varieties Cachaco, Mbwazirume, and Williams in the 5 different regions.



**Figure7**: Average crop cycle in Growing Degree Days (GDD) of the 3 varieties Cachaco, Mbwazirume, and Williams in the 5 different regions.



**Figure 8**: Average yield of the 3 varieties in the 5 different regions.

## Results Framework

| **Output** | **Indicative Indicators** | **Publications** |
| --- | --- | --- |
| **Output 1:**  Growth potential assessed | * Ranking of the growth potential of 105 banana genotypes under simulated highland conditions and identification of 21 “climate smart” varieties. | van Wesemael, J., Swennen, R., Roux, N., Carpentier, S. (2020). The importance of the light spectrum in a high-throughput phenotyping lab concept: evaluating transpiration and biomass growth of different banana cultivars under different blue/red light ratios. Acta Horticulturae 13-20 doi: 10.17660/ActaHortic.2020.1272.2 |
| **Output 2:**  Differential growth patterns studied in detail | * 32 varieties have been evaluated under osmotic stress conditions. The publication is available to breeders and researchers through open access (van Wesemael et al., 2019). * 15 varieties have been phenotyped in detail on the high throughput phenotyping platform Phenodyn (Collaboration with INRA in EPPN 2020 EU project; Eyland et al in preparation). * Stomatal conductance mechanisms of 5 varieties has been studied in detail and submitted for publication (Eyland et al submitted). | van Wesemael, J., Kissel, E., Eyland, D., Lawson, T., Swennen, R., Carpentier, S. (2019). Using Growth and Transpiration Phenotyping Under Controlled Conditions to Select Water Efficient Banana Genotypes. FRONTIERS IN PLANT SCIENCE, 10, Art.No. ARTN 352. doi: 10.3389/fpls.2019.00352  Eyland, D., Breton, C., Sardos, J., Kallow, S., Panis, B., Swennen, R., Paofa, J., Tardieu, F., Welcker, C., Janssens, S.B. and Carpentier, S.C. (2020), Filling the gaps in gene banks: Collecting, characterizing and phenotyping wild banana relatives of Papua new guinea. Crop Sci. doi:10.1002/csc2.20320 |
| **Output 3:**  Variety evaluation in the field and validation of lab models | * Field evaluation of 3 varieties at 5 locations (Tanzania and Uganda). (Machida et al in preparation) * Field evaluation of 4 varieties in Tanzania for 2 crop cycles. (Uwimana et al submitted) * Technical guidelines for lab and field phenotyping have been developed for local research stations and will be promoted via Musanet. | Carpentier, S., Iyyakutty, R.,Kissel, E.,van Wesemael, J. Tomekpe, K., Roux, N., Dita, M. (in press). Phenotyping protocol for drought tolerance in banana. Musanet  Carpentier, S. Eyland, D. (in press) Genetic approaches to improve abiotic stress factors in banana. In: Achieving sustainable cultivation of bananas Vol 2: Germplasm and genetic improvement (ed. Prof Gert Kema & Prof André Drenth)  Brown, A., Carpentier, S. C., & Swennen, R. (2020). Breeding Climate-Resilient Bananas. In Genomic Designing of Climate-Smart Fruit Crops (pp. 91-115). Springer, Cham. doi:10.1007/978-3-319-97946-5\_4 |
| **Output 4:**  Molecular mechanisms behind drought tolerance analyzed | * From a sub-sample of 12 and 36 varieties respectively the molecular and genetic analysis have been published (Cenci et al., 2019; Cenci et al., 2020). List of candidate alleles have been selected, genome recombination signatures and chromosome losses have been detected. * Researchers have open access to transcriptomic data publicly accessible in scientific databases. | Cenci, A., Hueber, Y., Zorrilla, J., van Wesemael, J., Kissel, E., Gislard, M., Sardos, M., Swennen, R., Roux, N., Carpentier, S.C., Rouard, M. (2019). Effect of paleopolyploidy and allopolyploidy on gene expression in banana. BMC GENOMICS, 20 (244), 1-12. doi: 10.1186/s12864-019-5618-0  Cenci, A., Sardos, J., Hueber, Y., Martin, G., Breton, C., Roux, N., Carpentier, S., Rouard, M. (2020). Unravelling the complex story of intergenomic recombination in ABB allotriploid bananas. Annals of Botany. Doi: 10.1093/aob/mcaa032  van Wesemael, J., Hueber, Y., Kissel, E., Campos, N., Swennen, R., Carpentier, S. (2018). Homeolog expression analysis in an allotriploid non-model crop via integration of transcriptomics and proteomics. Scientific Reports, 8, Art.No. 1353. doi: 10.1038/s41598-018-19684-5  Carpentier, S. C. (2020). The Use of Proteomics in Search of Allele-Specific Proteins in (Allo) polyploid Crops. In Plant Proteomics (pp. 297-308). Humana, New York, NY. |
| **Output 5:**  New knowledge shared with stakeholders (breeders and researchers) in the Great Lake Area (i.e., generated knowledge feeds into banana breeding and planting material supply chain) | * Publications and setup of the databases linked to MGIS[[4]](#footnote-4) and Musabase[[5]](#footnote-5). * PhD started:   + David Eyland (BE): Crop wild relatives: wild banana the key to drought tolerance?   + Clara Gambart (BE): The fundaments of crop growth: modelling growth and guard cell physiology in relation to light, vapor pressure deficit and soil water potential   + Noel Madala (TZ): End-users’ traits preferences for improved banana cultivars in Tanzania and Uganda * Master dissertation started at KU Leuven:   + MSc Marlies Vanluchene: 'Exploring nitrogen use efficiency of banana in the Bananatainer and the greenhouse' | PhD thesis Jelle van Wesemael: van Wesemael, J., Swennen, R. , Carpentier, S. (2019). Mining the Musa biodiversity for drought tolerance: allele discovery via integrated phenomics, proteomics and transcriptomics.  Master thesis Bill Smeets: Smeets, Bill. Understanding Water Deficit Response in Bananas: Screening Beneficial Traits in Wild Relatives by Phenotyping Root Properties, Leaf Emergence and Transpiration Dynamics. Leuven: KU Leuven. Faculteit Bio-ingenieurswetenschappen, 2020. Web. |

# 2021 Project prolongation and future potential

## Work plan

The proposed work is a one-year extension of the project executed in 2017-2020. While the former project dealt mainly with the high throughput screening of the accession from the banana gene bank, the analysis of the local diversity, and the multi-location field evaluation of 3 reference varieties, this next phase will **(i)** disseminate our results by releasing the phenotypic information on the gene bank web platform[[6]](#footnote-6) and continue capacity building, **(ii)** continue the **high throughput phenotyping** in the Bananatainer coupled to the molecular analysis to **characterize** their **unique genome composition and transcriptome and proteome profiles,** **(iii)** **assess the performance** of the 21 selected varieties **under real field conditions** by initiating a field trial, and **(iv)** conduct **key informant interviews with stakeholders** in different regions regarding varieties, climate change, and its effects on banana growing, and assess the possibility to **increase the digital inclusion** and to apply the tools developed by our digital inclusion team (Van Etten et al., 2019) in order to ensure availability of tools to manage risks associated with climate change and to support decision making for each region. Implementation of the key findings of the proposed experiments will take advantage of existing **farmer field schools initiatives** in close collaboration with National Agricultural Research centers and cooperation agencies **in the Great Lakes region**. We anticipate that our experimental design will provide data to improve and optimize tools for **farm management advice.**

## Dissemination of the results of the previous project phase and continuation of the capacity building

In 2021, the CGIAR team, the “Katholieke Universiteit Leuven” (KU Leuven), and the national agricultural research organizations (NARO Uganda and TARI Tanzania, RAB Rwanda) will closely collaborate to further disseminate and integrate the knowledge and data gained from the experiments under controlled conditions and the multisite field trials of our reference varieties. Such a multi-faceted variety evaluation is a considerable investment. Hence, we will maximize the spread and use of these data by sharing the knowledge of temperature dependent growth responses of all the phenotyped gene bank accessions via the Musa Germplasm Information System (MGIS), the specific gene characterization will further be integrated in the Banana Genome Hub and the multi-location trial data will be entered and shared on Musabase[[7]](#footnote-7). This will ensure the information reaches diverse target audiences. Moreover, we will not only passively make them open access but we will also actively promote them and pass on the knowledge using multiple channels. We will disseminate our published phenotyping protocols via MusaNet and Promusa to the local research communities. We will **train** local Master’s students and researchers from the national agricultural research organizations in phenotyping and we will set up **demonstration plots for farmers[[8]](#footnote-8)** in partnership with the national agricultural research organizations. We will take advantage of the existing data and update them with new data sets. This new expert knowledge will be fed into the stakeholder participation (see section 5). This supports the decision-making in banana farming for agro-input suppliers, cooperatives, agricultural extension organizations, and NGOs.

1. Evaluation of the most important transpiration related traits for use in farmers’ field: continuation of high throughput phenotyping (Bananatainer) and molecular analysis.

This part of the project builds on the knowledge gained so far during the climate simulations and high throughput phenotyping. Whole plant responses in agronomic reality are a complex interplay between genotype, environment, and management. Dissecting these multifactorial interactions allowed us to study more comprehensible traits with direct environmental responses. We identified risk taking highly transpiring varieties that appear vulnerable under water deficit (van Wesemael et al., 2019). Management practices like irrigation are the only way to alleviate the impact of the deficit. Otherwise production could be impacted adversely and other cultivars would have been a better choice. We also identified more conservative varieties that reduce their transpiration when water becomes limited (van Wesemael et al., 2019). Those varieties avoid and/or tolerate more severe deficits, and could be suitable in more extensive farming setups. However, these recommendations need further evaluation to refine our comprehensive knowledge base upon which climate smart cultivar selection is rationalized. We aim at identifying the correlation between stomatal and hydraulic conductivity in different environmental conditions and extrapolating these new insights to plant growth. These novel insights are key to understand how plant growth will be affected under the future challenging climatic conditions of reduced water availability and different temperature regimes. Therefore the high throughput phenotyping of the ITC gene bank in the Bananatainer will be continued.

## Assessment under field conditions

We will complement the key findings of the high throughput phenotyping by starting an *in situ* field experiment with the 21 promising varieties and the local controls (locally grown banana genotypes) for direct comparison of performance and demonstration for farmers.

The 21 varieties that were **predicted** to be valuable for cultivation in the highlands based on the Bananatainer experiments will be planted **on-site** next to the local controls.

Screening bananas in the field is challenging as it involves detailed and careful planning to accommodate different varieties with variations in crop duration. Therefore, we will plan the experiment carefully so that the field trial design will allow us to study tolerance traits during the important critical stages in the development of the banana plants (Gibbs and Turner, 2018). The life cycle of bananas can be divided into 3 phases: the vegetative, floral, and fruit phase (Figure 9). At the start of the floral phase, the apex changes from leaf formation towards the formation of the inflorescence. During this crucial floral phase, the development of the female flowers inside the pseudostem spans 12 to 13 weeks in the tropics and is up to twice as long in the sub-tropics. Any short-term effect of environmental conditions during this time will reflect in the shape and anatomy of the fruit. This phase can thus only be tested in the field. The floral phase is the most vulnerable as there is a competition for resources between the developing bunch, growth of emerging leaves, and elongation of the floral stem. Any disturbing environmental factor during the floral phase will prolong the crop cycle and will inevitably reduce the yield as the number of fruits per hand is directly affected (Gibbs and Turner, 2018). A disturbing environmental factor during the fruit phase affects fruit filling and reduces hand size and weight. Late flower abortion might also influence the number of fruits per hand.



**Figure 9:** Crop and ratoon cycle of banana in the highlands (Calculated in the average over the 5 locations -Luwero, Mbarara, Bukoba, Rungwe and Moshi). Commercial bananas in the wet tropics complete their cycle in 12 months (Turner, 1995). Phases vulnerable to drought are the floral phase (from flowering initiation to bunch emergence) and the fruit phase.

## Key informant interviews and increasing the digital inclusion for farmers

As stated above, we will perform on station field testing of 21 promising varieties coming from the ITC gene bank available in Leuven. However, as explained above, it is crucial that there is a demand for them on the local market. Different varieties produce bananas with different properties. We will therefore conduct further socio-economic studies to investigate the market potential and improve the distribution and the adoption of alternative banana varieties. Moreover, we will assess their consumer acceptance and assess their possible introduction in selected strategic agro-eco zones.

Furthermore, the ITC gene bank is not the only source of valuable diversity. Many local varieties are not commonly known nor distributed across regions/countries, and are currently not in the ITC collection or the regional germplasm collection in Mbarara (Kamira et al., 2016; Ocimati et al., 2014; Turner et al., 2016). It is essential to evaluate them for agronomical performance and acceptance across regions. However, evaluating different varieties across different regions is very challenging. **The progress we can make depends on the innovation capacity of farmers themselves**. Therefore, we build our project around this farmer central approach. Digital inclusion initiatives break down barriers to mobile internet adoption through infrastructure and policy, affordability, digital literacy and availability of local content. They contribute directly to poverty reduction and food security. Using a new technology called Progressive Web App, FAO has therefore developed four apps to scale up agricultural services. A novel citizen science methodology was also successfully implemented by Bioversity in India, East Africa, and Central America: triadic comparisons of technologies or ‘tricot’ on barley, durum wheat, and common bean (Van Etten et al., 2019). This methodology involves distributing agricultural technologies to individual farmers who embrace these technologies and use them to evaluate their varieties on their own farm. This ‘tricot’ approach is relatively easy to execute and farmers do not need to be organized in collaborative groups. Feedback is simply collected by phone. The idea behind the recent citizen science approaches is that large tasks can be accomplished by distributing small simple tasks to many volunteers. It creates a mechanism to break a large challenging task such as multi-variety evaluation on multi-locations into ‘micro-tasks’, and it generates mechanisms to retrieve and combine the results to accomplish the original complex task. Control over individual tasks is weak. Individual farmers will make mistakes. However, the built-in redundancy coming from the number of volunteers minimizes this risk. Each tasks is executed more than once by several participants. Farmers do not score the varieties, but rank them for different aspects of performance, including agronomic traits, yield, consumption value and overall performance. Trial data analysis makes use of complementary environmental data. Since the data are digitally collected, the trial points or points near the farmer’s plots are geo-located. This also makes it possible to combine the trial data with geospatial data from other sources. Another important advantage is that many environments are being sampled. Results from different participants at the same agro-zone are compared and filtered for quality by checking the consistency. The tricot approach provides interpretable, meaningful results and was proven in a pilot study to be widely accepted by farmers (Van Etten et al., 2019). Hundreds of farmers become in this way our ‘phenotypers’. As illustrated above, the yield of banana is a long-term response. During this project prolongation, only the gathering of information about the local variety usage linked to GPS and weather data will be realized together with the willingness to accept and try novel varieties.

# Outcomes and impact

This project extension proposes to build on the complimentary multidisciplinary expertise and available infrastructure in Belgium and Uganda. The synergies between the different partners will warrant progress in the deployment of improved varieties for increased food security. The integration of both socio-cultural, agricultural, and biotechnological aspects of the banana value chain will provide fundamental research evidence and contribute to improved outcomes of the different value chain actors. The project targets small- and medium-sized farmers, producing bananas for home consumption and local/regional markets in the African Great Lakes Region. Building on the experience and scientific excellence of the Bioversity-KU Leuven research team, the project will help to increase productivity and resilience of banana farms, through identifying varieties in the gene bank and from local environments that are better-adapted to climate related stresses.

In a later stage, key local varieties need to be safely backed up and **conserved** at the Mbarara germplasm collection and in the International Transit Centre (ITC). The *In situ* conservation ensures **local** **capacity building** for easy **access of good and healthy planting material and production of ‘seed’ for local business** while the *ex situ* conservation provides a secure backup in case of unforeseen natural disasters and anthropological conflicts. As previously demonstrated (Kilwinger et al., 2020), there is a good opportunity to improve the ‘seed business’ in the region. This work will serve also the **pre-breeding workflow** where valuable sub-traits and genetic information on existing varieties will nurture the local breeding programs (NARO, TARI, IITA).

Ultimately the insights into the potential of alternative selected banana varieties identified in the current research project will be instrumental in developing an action plan for rapid adoption of improved varieties by millions of **banana growers**. The generated data will also be incorporated in the farm management advice to sustain banana production in ecozones where populations face food security issues. The established network of digitally connected farmers is therefore very valuable. Within and beyond the target regions, this project intends to boost banana yields and livelihoods by **delivering suitable planting material** and implement the **tools for** **digital inclusiveness and** **train farmers in best practices for farm management**. The opportunity to increase the diversity in smallholder fields by adding healthy and locally adapted planting material to their portfolio will **mitigate the risk of yield loss due to unpredictable rainy seasons**. Our molecular and genetic work on the selected varieties will also provide breeders with tools to speed up banana breeding. For this to happen, key stakeholders (breeders, agronomists, social scientists, seed producers, agro-input traders, extension workers, etc.) will play important roles in **setting up local businesses** for delivering the agro-eco zone specific varieties to farmers in close collaboration with the socio-economic component of the research project.

We are committed to devoting a substantial part of our research for development activities to the cross-cutting theme of climate change, focusing on climate-smart agriculture based on urgently needed adaptation options for farmers. The generating and sharing of knowledge that will help poor populations to establish resilient banana production systems, will reduce the vulnerability to the effects of current and future drought on banana production and will ultimately strengthen the adaptive capacity to climate-related hazards and natural disasters.

| **Output** | **Indicative Indicators** |
| --- | --- |
| **Output 1:**  Results disseminated and knowledge shared | * Datasets on web portals * Workshops (on site and/or virtual) * Open access publications |
| **Output 2:**  Set of additional crucial varieties in the gene bank are evaluated and characterized | * Datasets on web portals * Open access publication * Availability of material for distribution |
| **Output 3:**  Field with 21 varieties plus controls is established | * Growth of the genotypes in response of real field conditions for the vegetative stage is quantified |
| **Output 4:**  Market study of trait preferences is performed and ‘tricot’ approach initiated identifying potential local varieties | * Open access publication * Network of farmers in different ecozones * List of local variety usage and their preferred traits |

**Sustainable Development Goals (SDGs) and System-Level Outcomes (SLOs)**

All members of the United Nation adopted the 17 Sustainable Development Goals (SDGs) in 2015 with the common aim to end poverty, protect the planet and to improve the world we live in by 2030. The CGIAR held governance reforms in 2016, and the Strategy & Results Framework (SRF) 2016-2030 was put forward to join all stakeholders to proactively manage a necessary evolution and tackle the rising issues in the increasingly hostile environmental conditions. The essence of the SRF encapsulates a number of the SDGs set out by the UN, and the end date was purposely aligned with those of the SDGs. In answering to the universal call to action of the United National Development Programme (UNDP), CGIAR has highlighted the spirit of partnership and integrated action. Backed by the proven track record of expertise of its fifteen Centres worldwide, including Bioversity International, CGIAR has defined three System-Level Outcomes (SLOs), namely 1) reduced poverty, 2) improved food and nutrition security, and 3) improved natural resources and ecosystem services. The research described in this proposal responds directly to all three SLOs, while contributing to SDG 1: no poverty, SDG 2: zero hunger, SDG 12: responsible consumption and production, SDG 13 climate action, besides SDG 5: gender equality, and SDG 17: partnerships for the goals.

Approximately one in ten of the world’s population currently live in poverty, and almost 690 million people in the world, i.e. 8.9% of the world population, are acutely or chronically undernourished (The state of food security abd nutrition in the world, 2020). Women and children remain disadvantaged and vulnerable across-the-board. At the same time overexploitation has led to an estimated 3.5 billion hectares land degraded and unproductive.

The CGIAR has made it its mission to advance agricultural science and innovation to enable poor people, especially women, to better nourish their families, and improve productivity and resilience so they can share in economic growth and manage natural resources in the face of climate change and other challenges. CGIAR’s disbursements has been found to translate to benefits twice the costs, and even as high as 17 times when harvested over the lifetime of projects (Renkow, 2010).

Godfray and co-authors have argued that “sustainable intensification” should replace a singled-out factor such as increased food output or changed diet, instead, multiple strategies in all fronts need to be incorporated simutaneously (Godfray, 2014). In many African countries such as Uganda, Rwanda, and Cameroo, banana consumption exceeds 200 kg per capita where particularly in rural areas, all types including non-Cavendish and plantains can provide up to 25% of the daily calorie intake. In order to satisfy the growing demand, banana producing countries have so far mainly increased the harvest area, along with better irrigation systems, higher application of fertilizers, phytosanitary measures and pesticides. Many of these methods come accompanied by negative ramifications. As leaders at the UN, the World Health Organisation (WHO) (Andersen), and WWF International (Lambertini) have recently warned, pandemics such as the COVID-19 outbreak resulting in major social, financial and health devastation, are more likely under the current rampant destruction of the natural world. Conversely, agri-food system research, specifically climate-smart agriculture, is an effective investment to end poverty and hunger, and will at the same time improve natural resources and ecosystem services. Our research is well-placed to provide solutions to SDG 2: zero hunger and SLO 2) improved food and nutrition security, SDG 12: responsible consumption and production, SDG 13: climate action and SLO 3) improved natural resources and ecosystem services, and eventually SDG 1: no poverty and SLO 1) reduced poverty. This is because bananas provide household food security and generate income as a cash crop in some of the least developed and low-income food-deficit countries (FAOUN, n.d.). According to a study by Bioversity, 75% of the total monthly household income for smallholder farmers is attributed to banana farming. When smallholders have access to the banana varieties most suited for specific growth conditions, a greater quantity of banana as an affordable staple food source is produced, impacting on the micro- and macroeconomic systems.

Further, our research is a collaboration of various countries: Uganda, Tanzania, Rwanda, and Belgium and different institutes and players: the National Agricultural Research Organisation (NARO), Tanzanian Agricultural Research Institute (TARI), the International Institute of Tropical Agriculture (IITA), KU Leuven, and Bioversity as well as the inclusion of the citizen science approach, and it covers the geographical area of Africa’s Great Lakes Region. This is a prime example of “integrated solutions” and the “Leave No One Behind” pledge of the UNDP, where member countries have committed to fast-track progress for those furthest behind first, delivering SDG 17: partnership for the goals.

Our proposal moreover includes an associate scientist to develop a detailed analysis of the gender-specific needs, supporting SDG 5: gender equality.

The extension of the support of Foreign Affairs of Belgium for this project will send a clear message of Belgium’s determination to honour the pledge in response to the 17 SDGs of UNDP. Equally significant, the continuing involvement of the Belgian government will reaffirm Belgium’s active position in the international development arena.

## Resources

Specific funding will be required for the following:

### Coordination of the project

**Project leader** will manage the project and be responsible for the project implementation, dissemination of the results, and supervision of the staff and students.

### Socio-economic market analysis and Tricot

**Associate scientist** will oversee the local demand and business opportunities to develop a more detailed analysis of the **gender-specific needs** and the uniqueness of the local varieties and will liaise with collaborating institutes. Local volunteers for the Tricot study will be recruited.

### Field work and Tricot (strengthen the local capacity building)

**Scientist** will help the team leader by being the local responsible for the field trials, the data collection, and **digitizing** (uploading in the breeding database) and will draft the manuscripts for publication of the results.

**Technician** will help the scientist with the field work and data collection.

**Student** of the Makerere University will help the scientist and the project leader in setting up the phenotyping experiments and in interpreting and **validating** the data.

### High throughput phenotyping

**Technicians** will order the varieties from the gene bank, multiply the plants for the Bananatainer, maintain the Bananatainer, and collect the data.

**PhD student** will help the project leader in setting up the phenotyping experiments and in interpreting and validating the data.

**Data analyst** will help the project leader in setting up the phenotyping experiments and interpreting and in validating the data.

### Genome analyses and bioinformatics

**Associate scientist** will analyze the data of the lab phenotyping and the genetics of the potential local varieties, and will draft the manuscripts for publication of the results.

**Scientist** will help the project leader by being the local responsible to supervise genome analyses work and **digitizing** (uploading the data onto the gene bank and genomic databases), and will work with the associate scientist and project leader to draft and review manuscripts.

### Consumables and travel

Budget for travel between Belgium and Uganda and consumables for the Bananatainer, molecular/genetic analysis and the Tricot setup is needed.

|  |  |
| --- | --- |
| **Details** | **TOTAL BUDGET** |
|
| Personnel | 170,250 |
| Supplies and Services | 10,000 |
| Staff Duty Travel | 10,000 |
| Collaboration and Partnership with KULeuven | 300,000 |
| Research Support Services and Facilities | 96,727 |
| Indirect Costs | 99,023 |
| CSP | 14,000 |
| **TOTAL in EURO** | **700,000** |

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1. http://www.promusa.org/Taxonomic+Reference+Collection [↑](#footnote-ref-1)
2. https://www.crop-diversity.org/mgis/gigwa [↑](#footnote-ref-2)
3. This work is in support of the Bill and Melinda Gates project Breeding Better Bananas and is a collaboration between the CGIAR, the National Agricultural Research Organisation from Uganda (NARO), and the Tanzanian Agricultural Research Institute (TARI). [↑](#footnote-ref-3)
4. https://www.crop-diversity.org/mgis/ [↑](#footnote-ref-4)
5. https://musabase.org/ [↑](#footnote-ref-5)
6. https://www.crop-diversity.org/mgis/phenotyping-studies [↑](#footnote-ref-6)
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