IFPRI Discussion Paper 01927

May 2020

Benefits from the Adoption of Genetically Engineered Innovations in the Ugandan Banana and Cassava Sectors

An Ex Ante Analysis

Enoch Mutebi Kikulwe

Jose Falck-Zepeda

Herbert Oloka

Judy Chambers

John Komen

Patricia Zambrano

Ulrike Wood-Sichra

Hillary Hanson

Environment and Production Technology Division

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

AUTHORS

Enoch Mutebi Kikulwe (e.kikulwe@cgiar.org) is a local lead economist for BioRAPP and Scientist, Alliance of Bioversity International and CIAT, Kampala, Uganda.

Jose Falck-Zepeda (j.falck-zepeda@cgiar.org) is a Senior Research Fellow in the Environment and Production Technology Division of the International Food Policy Research Institute (IFPRI), Washington DC.

Herbert Oloka (H.Oloka@aa-bs.co.ug) is Uganda Country Coordinator for PBS/BioRAPP, Kampala, Uganda.

Judy Chambers (j.chambers@cgiar.org) is Program Director of PBS/BioRAPP in IFPRI's Environment and Production Technology Division, Washington DC.

John Komen (jce.komen@planet.nl), is PBS Lead Africa Strategist, De Haag, Netherlands.

Patricia Zambrano (a.p.zambrano@cgiar.org) is Senior Program Manager in IFPRI's Environment and Production Technology Division, Washington, DC.

Ulrike Wood-Sichra (u.wood-sichra@cgiar.org) is a Senior Research Analyst in IFPRI's Environment and Production Technology Division, Washington, DC.

Hillary Hanson (hyhanson@gmail.com) was Program Coordinator in IFPRI's Environment and Production Technology Division, Washington, DC, at the time of producing this discussion paper. She is now at the International Foundation for Electoral Systems (IFES).

Contents

List of Tables

List of Figures

Abstract

The Government of Uganda has implemented programs and policies to improve the agricultural sector's recent underperformance. Uganda's two main food security crops, bananas and cassava, have been critically affected by two diseases: Banana Xanthomonas Wilt (BXW) and Cassava Brown Streak Disease (CBSD). The effectiveness of agronomic and cultural practices to control these diseases has been limited, requiring better alternatives. The Ugandan R&D sector in collaboration with international partners have developed genetically engineered innovations that can control both diseases. To examine the potential benefits to consumers and producers from the adoption of genetically engineered banana and cassava with resistance to BXW and CBSD, we use a set of economic impact assessment methods. These include an economic surplus model implemented via IFPRI's DREAMpy framework, a real options model and a limited gender assessment. Results from the economic surplus approach suggest that the adoption of both technologies can benefit Uganda. These results were confirmed for the case of bananas and partially for the case of cassava using the real options and the gender assessment performed. Results from this assessment are predicated on Uganda maintaining an enabling environment that will ensure the deployment and use of both innovations. Looking forward, continuing to improve enabling environment for innovation in Uganda will require addressing current R&D, regulatory, technology deployment and product stewardship processes constraints.

Key Words: Bananas, Cassava, *ex ante* economic impact, Uganda, Cassava Brown Streak Disease, Banana Xanthomonas Wilt

Acknowledgements

We gratefully acknowledge the contribution from our partners at the Ugandan National Council of Science and Technology (UNCST), the Ugandan National Agricultural Research Organization (NARO) researchers, Ministry of Agriculture-Animal Industry and Fisheries , Ministry for Science-Technology and Innovations, National Planning Authority, National Crops Resources Research Institute – Namulonge, , and crop and technology experts in Uganda and from the African Agricultural Technology Foundation (AATF) and International Maize and Wheat Improvement Center (CIMMYT in Spanish), Uganda Biotechnology and Biosafety Consortium (UBBC), and the Open Forum for Agricultural Biotechnology (OFAB).

Their inputs were critical in defining the research project and producing all estimations presented in this document. We specially acknowledge the support of Bioversity International who continues to work on supporting banana improvement in Uganda. This work was undertaken as part of the Biotechnology and Biosafety Rapid Assessment and Policy Platform (BioRAPP), a project led by IFPRI's Program for Biosafety Systems (PBS). BioRAPP is a project co-funded by the Bill and Melinda Gates Foundation, USAID and the IFPRI-led CGIAR Research Program on Policies, Institutions, and Markets (PIM).

We particularly acknowledge the contribution of crop, policy and technology experts within Uganda particularly those from Dr. Wilberforce Tushmereirwe, Dr. Titus Alicai, Dr. Anton Bua, Dr. Robert Kawuki, Dr. Henry Wagaba, Dr. Jerome Kubiriba, Dr. Kenneth Akankwasa and Dr. Walter Ocimati for their valuable insights during the data collection and implementation, analysis and pressure testing preliminary results from this project. The project also benefited from research assistantship of James Muhangi. We acknowledge the support and advise of and Donna Ramaeker-Zahn, PBS Outreach Strategist, who provided timely and valuable support and advice. We also received valuable feedback on modeling scenarios and early results from Stanley Wood (Bill and Melinda Gates Foundation) and a style editor at IFPRI. We acknowledge the valuable anonymous review and copyediting done at IFPRI.

Acronyms

ASSP: Agriculture Sector Strategic Investment Plan

BioRAPP: Biotechnology and Biosafety Rapid Assessment and Policy Platform

BXW: Banana Xanthomonas Wilt

CBSD: Cassava Brown Streak Disease

CMD: Cassava Mosaic Disease

GE: Genetically Engineered

GMO: Genetically Modified Organism

IFPRI: International Food Policy Research Institute

MISTICs: Maximum Incremental Social Tolerable Irreversible Costs

NPV: Net Present Value

PBS: Program for Biosafety Systems

R&D: Research and Development

SIRBs: Social Incremental Reversible Benefits

TCVs: Transgenic Cassava Varieties

USAID: United State Agency for International Development

1. Introduction

Agriculture is a major component of Uganda's economy. Agriculture accounted for about 20 percent of Uganda's GDP in fiscal year 2017/2018 and 43 percent of export earnings (World Bank 2018; Feed the Future 2018). Data extracted from FAOSTAT (FAOSTAT 2020) shows that food crops remains an important component of the agricultural sector accounting for 63 percent of the total value of agricultural production in Uganda while having an important social role to the economy.

The social importance of agriculture and food crops in Uganda is tied to the number of smallholder subsistence farmers which constitute the largest share of its producers. Agriculture employs 70 percent of Uganda's labor force while providing income to rural households. Rural households include 40 percent of the poorest households in the country (Feed the Future 2018). Agricultural interventions can have an important role in addressing poverty and food insecurity in an agricultural economy. Uganda's agricultural production growth has been however 2 percent per year from 2005 to 2015 (UBOS 2010 and 2017a). Uganda's agriculture has not been meeting its productivity and production potential and thus its poverty addressing possibilities.

To overcome its agricultural sector underperformance, the Ugandan government has designed several policies and plans including Uganda's Vision 2040, the second Uganda national development plan (NDPII) and the Agriculture Sector Strategic Investment Plan (ASSP).[1] These policies and plans consider agriculture as a key sector for future economic growth resulting

[1] Priority crops in the ASSP include banana, beans, maize, rice, cassava, Irish potatoes, tea, coffee, fruits and vegetables, dairy, fish, meat and other livestock, cocoa, cotton, oil seeds, and oil palm (see https://www.agriculture.go.ug/agriculture-sector-strategic-plan-assp/)

from production and productivity increases and commercialization improvements across agricultural and related value chains.

Uganda's two most important food security crops – bananas and cassava – have been critical in helping feed its population.[2] In recent years, both cassava and banana have been threatened by the emergence and spread of destructive diseases. Banana *Xanthomonas* wilt (BXW) is predicted to destroy up to 90 percent of Ugandan bananas if not controlled (Ocimati et al., 2019; Blomme et al., 2014). BXW also threatens millions of farmers in Uganda with long-term negative impacts that include the death of mother plants that would otherwise contribute to new plantules development. As a consequence, farmers face gradually increasing losses over time (Tripathi et al., 2009; Karamura et al., 2010). In turn, cassava brown streak disease (CBSD) continues to damage cassava in farmers fields since it was first observed in 2004. The disease causes up to 100 percent yield loss in severely infected sites (Alicai et al., 2007). As reported in the most recent available estimate, Tomlinson et al (2017) indicates that CBSD prevalence in Uganda increased from 12 percent in 2008 to 27 percent in 2011. These values seem to be supported by a current field data compilation effort published by Alicai, Szyniszewska, and Omongo (2019). Similar prevalence levels have been observed in Tanzania and Kenya (Legg et al. 2011; Mware et al. 2009). Accordingly, CBSD has been ranked among the 100 most dangerous diseases in the world due to its impacts on yield in a food security crop (Abaca *et al.*, 2012).

[2] According to data extracted from FAOSTAT, in 2016, "plantains and others" represent 15 percent of total value of agricultural production, whereas "bananas" represent 3 percent and "cassava" 6 percent. Plantains and others, bananas and cassava represent a 37 percent of the total value of production of crop production in Uganda, excluding livestock, fiber, spices and stimulants.

While there is no chemical or biological agent that has demonstrated control effectiveness, there are limited control measures for managing both diseases (Geberewold 2019; Alicai et al. 2007). Efforts to address BXW have focused on cultural and agronomic practices including eliminating infected plants, enforcing on-farm phytosanitary measures, use disease-free planting materials, and quarantine which can have a positive impact if implemented in a proper manner (Ocimati et al. 2019). Cultural and agronomic efforts in bananas have had limited success as the disease often resurges as farmers become complacent in their implementation. Proactive measures have not been diligently applied, reducing their efficacy (Geberewold 2019). In cassava production, CBSD management options for CBSD are unfortunately limited to destruction of infected fields and use of clean planting materials to establish new fields.

In response to the threat presented by CBSD and BXW, the Ugandan government and the national and international research community have continued exploring alternatives for the control of both diseases. One of the most promising alternatives identified are genetically engineered (GE) approaches which attempts to introduce resistance in both crops. Use of GE approaches are a response to policy directives by the Ugandan government including the Uganda National Biotechnology and Biosafety Policy of 2008. This policy identified genetic engineering as an important R&D tool in realising the country's development potential in agriculture, healthcare, industry and environmental management (Uganda, Ministry of Finance, Planning and Economic Development 2008).

After years of research and development led by the Ugandan National Agricultural Research Organization (NARO) and others, GE varieties in both crops are approaching a stage where they can be released after compliance with biosafety and variety release procedures by relevant authorities in Uganda. To date, the safety and efficacy of both crops have been assessed by Ugandan authorities at multiple stages including laboratory, greenhouse and confined field trial stages. Ugandan national competent authority used scientific assessment protocols and globally accepted best practices per Uganda's relevant guidelines and policies.[3]

As these technologies approach final regulatory status and are poised for deployment to farmers, it is important to understand the economic value they may provide to Uganda through adoption and use. This is especially important given the current lack of balance in the debate focused on GE technologies in Uganda, where a discussion of risk and benefits from this technology coexist (UBIC, 2015).

This paper describes a comprehensive *ex ante* economic assessment conducted in Uganda by a team that included economists, developers, researchers, and crop experts. National organizations in Uganda including Uganda National Council for Science and Technology (UNCST), National Agricultural Research Organization (NARO) and relevant Ministries provided support for the assessments. The assessments in Uganda are part of a portfolio of *ex ante* assessments conducted in five countries in Africa under the Program for Biosafety Systems (PBS) and the Biotechnology Rapid Assessment Policy Platform (BioRAPP). Both PBS and BioRAPP are led by the International Food Policy Research Institute (IFPRI).[4] IFPRI's economists

[3] The competent national authority, The Uganda National Council of Science and Technology (UNCST), implemented the process and protocols for risk assessment of both BXW resistant bananas and CBSD resistant cassava. The process pursued is described in the containment and confinement guidelines (UNCST 2007, 2011) and the seed act supplement (UNCST 2006). These protocols for risk assessment are mandatory for applicants pursuing environmental release and are implemented to fulfill Uganda's obligations to conduct risk assessments of living modified organisms before environmental release as a party to the Cartagena Protocol on Biosafety.

[4] The PBS program and the BioRAPP project have been funded by the Bill and Melinda Gates Foundation, The US Agency for International Development (USAID), the IFPRI-led CGIAR Research Program on Policies, Institutions, and

and other international biotechnology and biosafety experts provided technical backstopping and support to the research.

This discussion paper describes the implementation of an economic surplus approach, using IFPRI's DREAMpy tool to provide economic impact estimates of potential GE bananas and cassava adoption in Uganda. We also pursued a real options model approach to address irreversibility, flexibility, and uncertainty in R&D investments in country relevant technologies to cross-check our results. We estimated gender differentiated outcomes for the case of bananas although preliminary due to data limitations. Results from the *ex ante* exercise considers a range of outcomes and an examination of the impact of research and development (R&D) and regulatory delays.

The discussion paper is organized as follows. First, we describe the country, crop and disease background. Second, we describe the methodological approach including data collection and model implementation. Third, we introduce results from the economic assessments while describing gaps, limitations and avenues for further research. Fourth, we discuss the current environment in Uganda, which may enable or hinder the deployment of the BXW resistant banana and the CBSD resistant cassava, including a discussion of policy implications with a focus on those issues that may limit accessing benefits described in the ex-ante economic assessment including institutional and innovation issues. We conclude with a summary and description of overall results.

Markets (PIM) and other donors. Implementation of PBS and BioRAPP has been done in close collaboration with national partners. The BioRAPP project has conducted eight ex ante assessments of specific GE crop technologies in Ethiopia, Ghana, Nigeria, Tanzania, and Uganda.

2. Country context

Uganda is a country of contrasts and opportunities for policy interventions. Uganda had an average annual economic growth rate from 2012 to 2017 of 4.5 percent. Yet, economic growth by sector for FY 2016/17 shows that agriculture, forestry and fishing sector registered the lowest growth rate at 1.6 percent compared to 3.3 percent and 5.7 percent in industry and services sectors, respectively (Uganda, Ministry of Finance Planning and Economic Development 2017). Concurrently, Uganda made remarkable progress towards reducing poverty, with the national poverty rate declining from 56.0 percent in 1992 to 19.7 percent in 2013. Since then, poverty levels have fortunately rebounded, increasing to approximately 21.4 percent (UBOS2017b).

For the agricultural sector to fulfill its expected role as one of Uganda's priority sectors, moving the economy to a low middle-income status by 2020, it would have required an annual growth rate of at least 6 percent since 2017 (Uganda, Ministry of Agriculture Animal Industry and Fisheries Uganda, 2017). Growth in the agriculture sector, however, has stagnated averaging at 1.9 percent since 2007/08 to date. The agricultural stagnation may be partly due to slow development and deployment of technological innovation, poor management of pests and diseases, limited access to land and agricultural finance, a weak agricultural extension system, as well as, an over dependency on rain-fed agriculture, declining terms of trade and price issues, and other institutional and governance issues (Bategeka, Kiiza and Kasirye, 2013). These determinants of agricultural growth may be augmented also by insufficient public expenditure on the agricultural sector. Public expenditures in the agricultural sector have fluctuated between 3 to 5 percent of the national budget, which is far less than the 10 percent recommended by the Comprehensive Africa Agriculture Development Programme (CAADP).

To enhance the agricultural sector's contribution to wealth and job creation, the need exists to address all critical gaps, including those described so far. In this discussion paper, we contribute evidence on the value of technology in supporting agricultural growth in the economy, using the case of cassava and banana in Uganda, which are the two most important staple crops in Uganda (FAOSTAT, 2020; USDA FEWSNET 2017).

Banana and cassava sub-sectors in Uganda

Bananas

Statistics computed from the FAOSTAT online database at the Food and Agriculture Organization (FAO) show that in 2018 Uganda had the second largest area harvested with bananas[5] in Africa with 21 percent of the total area under banana cultivation across Africa and 16 percent of production (FAOSTAT, 2020). Banana production in Uganda amounted to 4.6 million metric tons in 2014, of which 3,070 metric tons were exported. Ugandan banana exports where mostly to the United Kingdom and the European Union, with a small share exported to South Sudan and Kenya. The MIT Observatory of Economic Complexity estimates that bananas export value in 2017 for Uganda was US$4.4 million (Simoes and Hidalgo 2011).

[5] FAOSTAT provides separate statistics for "bananas" and for "plantains and others". Bananas refer to dessert bananas, while plantains and others in Uganda includes east highland bananas and others cultivated for matooke and other uses. FAOSTAT data used in text is for "plantains and others" only.

Box 1. The East African Highland Bananas

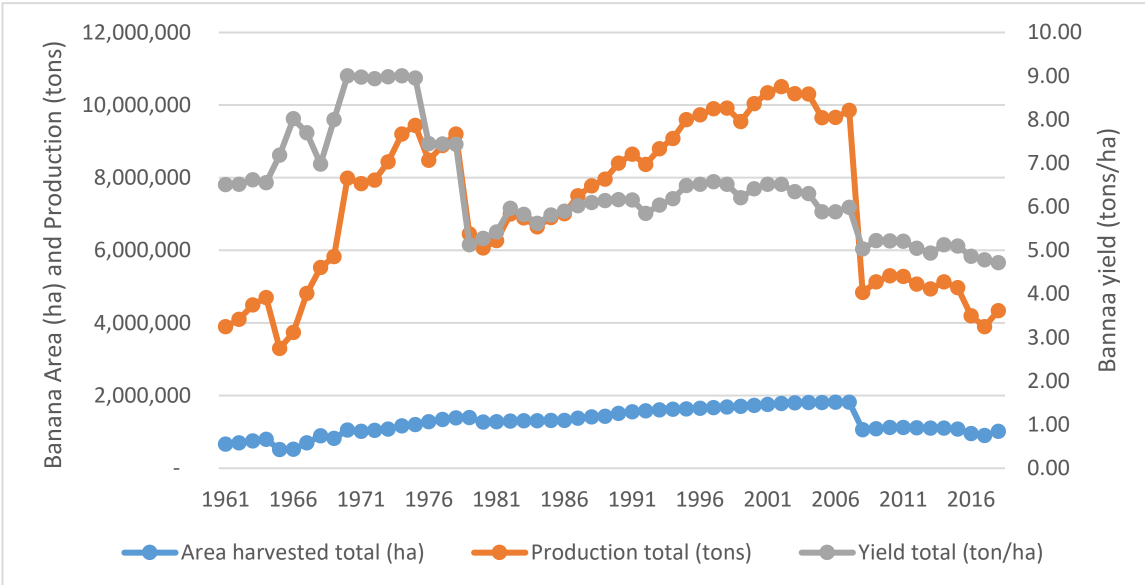
In Uganda, the most widely grown cultivars are cooking types belonging to the East African highland banana (EAHB). Other bananas grown in the country include dessert bananas ('Sukali Ndizi' and 'Bogoya'), Plantains for roasting ('Gonja') and beer bananas ('Kayinja' and 'Kisubi').

EAHB cultivars are largely grown in subsistence and smallholder systems at elevations of 1000 to 2000 meters. The 2008/2009 census found that 68 percent the banana crop was produced in the Western Region, Central Region (23 percent), the Eastern Region (8 percent) and the Northern Region (<1 percent).The Western Region had the highest yields (6 mt/ha) while the Central Region had the lowest ones (3.3 mt/ha).

Source*: Extracted from Promusa at http://www.promusa.org/Uganda*

Figure 1 introduces bananas production area, production and yield in Uganda from 1960 to 2017. Data was extracted from FAOSTAT. Yields reached a peak 5.33 tons/ha in 1994 decreasing steadily since then, down to 4.6 tons/ha in 2018. Yield decreases in Figure 1 (and Figure 2 below) cannot be attributed solely to plant pathogens such as BXW. Other reasons for the observed yield decrease include soil fertility declines, pests (nematodes, weevils) and moisture stresses as well as, institutional and market constraints such as input access and low prices (Nyombi 2013). Area harvested increased from 1961 through 2007 reaching a peak of 1.8 million hectares. Area harvested was just over 1 million hectares in 2018. Production increased from 6 million tons in 1980 to 10.5 million tons in 2002. Producing has been decreasing since 2002, reaching 4.3 million tons in 2018.

Figure 1 Banana production, area and yield in Uganda (1960-2018)

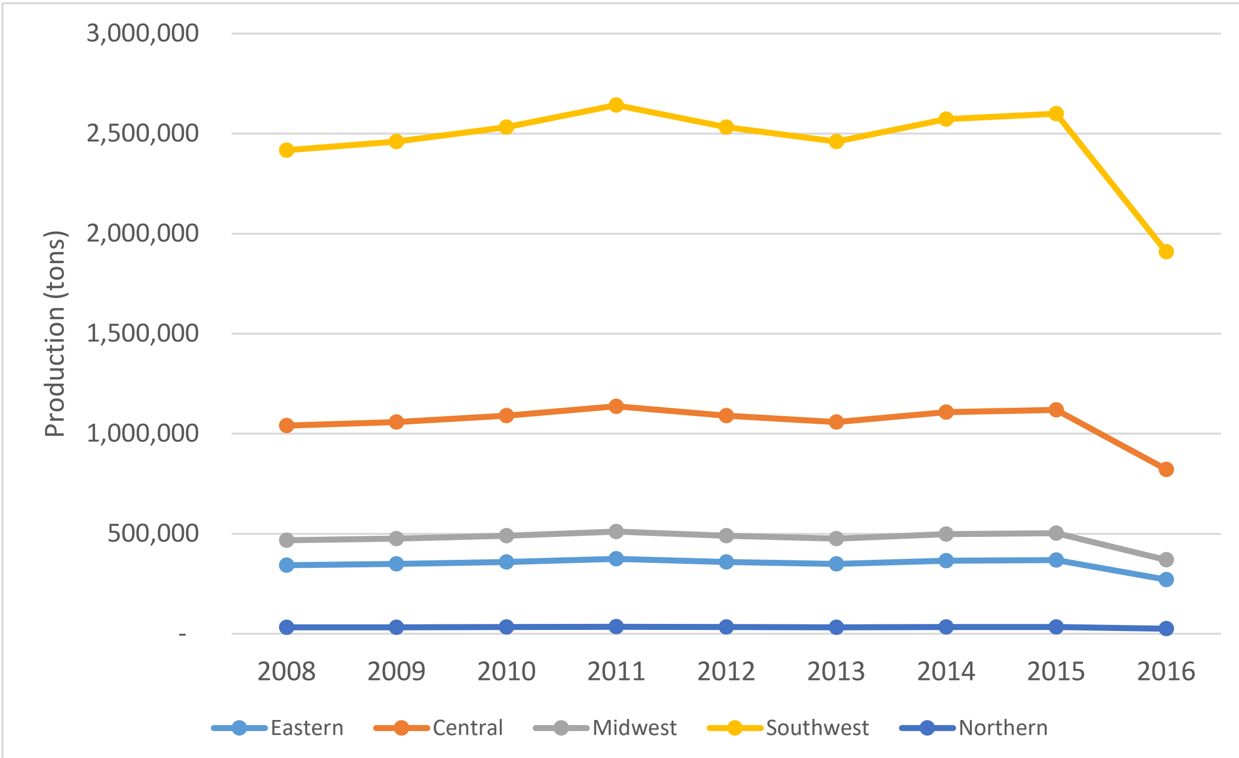


Source: FAOSTAT (2020)
Note: Banana statistics refer to bananas plus plantains and others in FAOSTAT. Banana yield is a weighted average of bananas and plantains, and others yields.

Figure 2. examines production in metric tons by region in Uganda. Overall, the Southwest region has the largest production, followed by Central, Midwest, and Eastern regions. Northern produces the smallest quantity of bananas in Uganda. Production has been decreasing since 2011 especially for the Southwestern region. Across all regions, area in this period has increased slightly but yields have in fact decreased significantly since 2011 (not shown here). These two factors drive production decreases over time.

Table 1 shows that Southwest has the highest production but also the lowest price for bananas. Central has the second largest production and a price that is in the middle of the prices spread in Uganda. Midwest has the highest price for bananas and the third largest production. These will have implications for the calculations in the economic surplus estimations.

Figure 2 Banana production by region in Uganda (2008-2016)



Source: UBOS (2017a, 2017b)

Table 1 Projected Uganda's banana production and value of production in 2018

Region	Price (1000UGX/ton)	Quantity (1000mt)	Value or Production (1000UGX)
Central	491	1,095	537,151,970
Eastern	439	360	158,141,504
Midwest	707	492	347,544,053
Northern	501	33	16,688,455
Southwest	346	2,544	880,980,512
Total for Uganda		4,524	1,940,506,493

Source: Projections using base year of 2015 from UBOS (2016, 2017a)

According to the MAAIF (Uganda, Ministry of Finance, Planning and Economic Development 2017a) the banana sector at the time was targeted to produce 13 million MT by 2020 through increased production and productivity of bananas by control of pests and diseases; generation and distribution of clean planting materials to farmers (i.e. through tissue culture); promoting the use of organic and inorganic fertilisers and soil moisture conservation techniques; strengthening extension services and training in good agricultural practices. This target implied substantial area and yield increases compared to 2017 levels.

Cassava

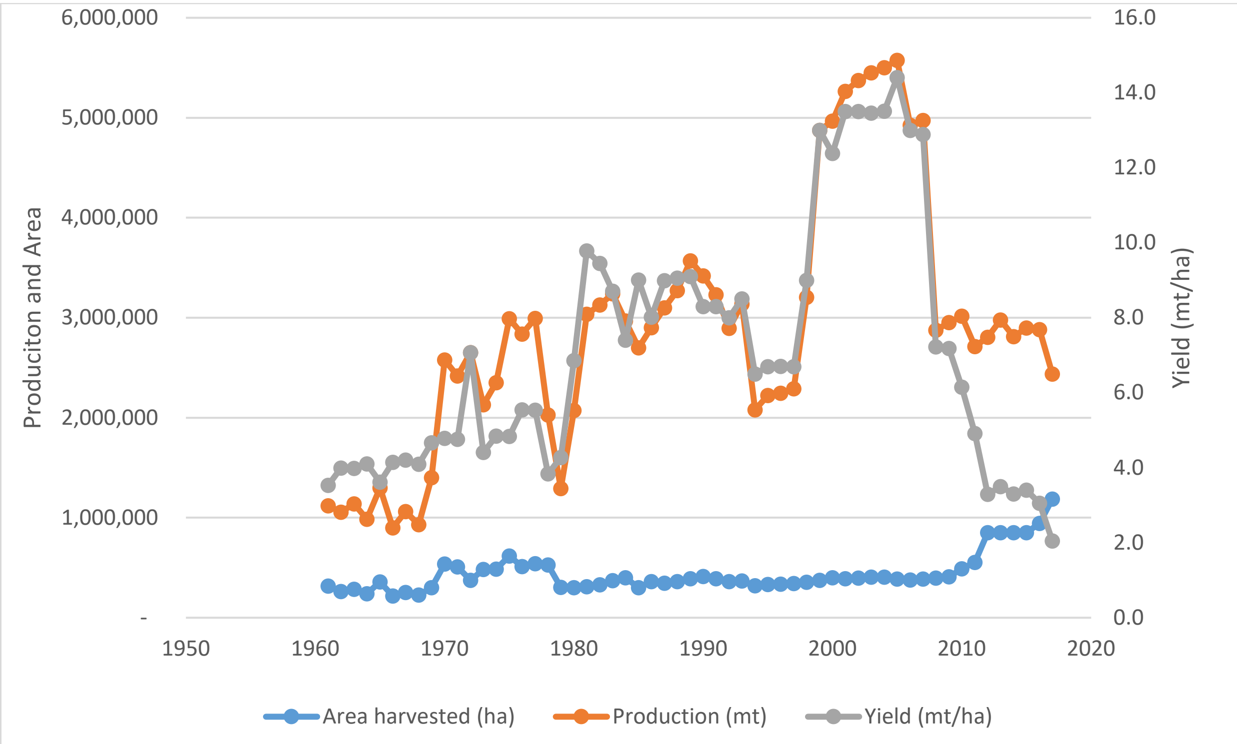
Uganda is among the top seven producers of cassava in Africa (FAOSTAT, 2020). The crop is an important staple with wide acceptability, significant and potential commercial contributions, and wide ecological adaptability in Uganda and in Africa in general (Sekabira *et* al., 2018; Feleke et al. 2013).[6] Cassava production amounted to 2.8 million MT in 2014. The MAAIF (Uganda, Ministry of Finance, Planning and Economic Development 2017a) indicated that the sector was targeted at the time to increase production of cassava to 3.5 million MT by 2020. To achieve the targeted production would have needed to increase area and/or yield per unit of area. This in turn implied that the sector would need to establish production and distribution of clean planting material resistant to crop pests and diseases, develop monitoring and diagnosis systems for pest and diseases; among other solutions (Uganda, Ministry of Finance, Planning and Economic Development 2017b).

Cassava production, area and yields in Uganda have fluctuated over time. As seen in Figure 3 the area harvested has increased to a maximum of 1.18 million hectares in 2017. Minimum area harvested was 216 thousand hectares in 1966. In turn, yields reached a maximum of 14.4 tons/ha in 2005, whereas the minimum observed yield was 2.1 mt/ha in 2017. The significant reduction in yields since 2005 induced a decrease in production, although

[6] For a general discussion about cassava's industrial potential in Uganda and Africa, see Annex 3.

the lowest production level occurred in 1966. As in Figure 1. The observed yield decreases cannot be attributed solely to CBSD. Observed yield decreases are likely to be the same issues that have constrained cassava yields over time including pathogens and other pests, poor access to inputs and extension services (Otim-Nape 2005).

Figure 3 Cassava production, area and yield in Uganda (1960-2017)



Source: FAOSTAT (2020)

The data presented in Table 2 are estimates for 2018 extracted from within the DREAMpy model which use baseline data from UBOS (2016). The projection described in Table 2 derived from baseline assumptions used in the DREAMpy modeling and baseline data from Uganda implies roughly 2.85 million tons of cassava production in Uganda with a value of production of 1.24 billion Ugandan Schillings in 2018. Eastern and Northern are the largest producer regions of cassava in Uganda. Price in these two regions are comparable to that of Central and higher than Western. Price dispersion is not as large in cassava as it is in bananas.

Table 2 Projected Uganda's cassava production and value of production in 2018

Region	Price (1000UGX/T)	Quantity (1000mt)	Value or Production (1000UGX)
Central	429	403	172,742
Eastern	467	1039	485,536
Northern	455	964	438,885
Western	325	441	143,312
Total for Uganda		2,846	1,240,475

Source: UBOS (2016 and 2017a)

The Banana and Cassava Diseases

Bananas Xanthomonas Wilt

Banana Xanthomonas Wilt (BXW) damage affects all banana types. National experts predict that BXW will destroy 90 percent of all bananas in Uganda if not controlled. BXW can completely decimate individual banana plots and thus heavily impact farmer's food security. To address BXW devastating impacts on farmers, the Ugandan government invested US$ 1.7 million to control BXW using agronomic and cultural over a 3-year period (Ocimati et al. 2019). The recommended control methods for BXW implemented in the 3-year program included: destruction and disposal of infected plants, disinfecting tools used in the plantation, using clean planting material and removing male buds.

The Ugandan government has also invested in banana improvement programs to improve resistance, as the use of resistant planting materials has been identified as one option for the effective control of BXW. The recommended portfolio of cultural practices to control the disease has been hampered by lack of knowledge about the disease and the portfolio of control practices and high labour costs for effective implementation (Tripathi, 2017).

In spite of the diversity of approaches used to reach out to farmers including the extension system, different media, cultural and local leaders, and a participatory development communication approach which consisted in organizing multiple stakeholders and experts (Bagamba et al. 2006, Ngambeki, Tushmereirwe and Okaasai 2006, Muhangi et al. 2006)[7] the fact still remains that agronomic and cultural practices need to be implemented in a rigorous manner. Failures in applying one or more component of the recommended control package may lead to disease spread. Resistance thus become a required complementary approach for BXW control.

Kagezi et al. (2006) speculates that the observed lower BXW incidence in the Southwestern region may be explained by East African Highland varieties are less prone to insect transmission and by the fact that farmers were already routinely removing the male bud for other reasons when the outbreak started. Box 2 introduces a timeline for BXW relevant events from first reports to indications that BXW may be endemic in Uganda and in fact the most prevalent disease in the country.

[7] A study by Kubiriba (2012) suggests farmer field schools may have been more effective in reducing BXW than traditional extension services and mass media.

Box 2. Banana Xanthomonas Wilt timeline in Uganda

- 2000 - Farmer unconfirmed first reports (Tushmereirwe et al 2003).
- 2001 - First formal report in Mukono district in the Central region (Tushemereirwe et al 2004)
- 2003 - Ministry of Agriculture Animal Industry and Fisheries (Uganda, Ministry of Agriculture, Animal Industry and Fisheries 2017) and the National Agricultural Research Organization (NARO) embarked on an intensive programme to raise awareness of the problem and enable farmers to identify the symptoms of the disease and to implement control measures (Tushmereirwe et al 2006).
- 2005-2006 Early disease reporting database established (Tushmereirwe 2006).
- 2005 Rapid spread through Central Uganda reaching major banana-producing areas in Southwestern region (Kagezi et al. 2006).
- 2006-2010- Analysis of plant clinic records diagnosing sick plant samples, showed that BXW was the most diagnosed disease overall, despite the massive efforts expanded to raise awareness on the disease (Danielsen et al 2013)

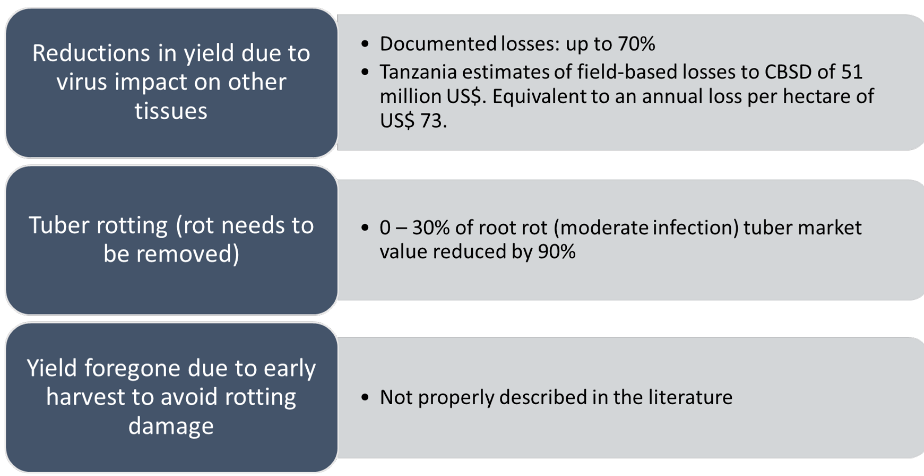
Source: Extracted from Promusa at http://www.promusa.org/Uganda

Cassava Brown Streak Disease (CBSD)

As shown in Figure 3 above, area planted to cassava has increased over time, but production has decreased. Falling yields since 2005 may be partially explained by the re-emergence of Cassava Brown Streak Disease (CBSD) and Cassava Mosaic Disease (CMD) but also from other pests, diseases and lack of intensification programs. Damage from CMD was observed in the early 1990s, and although considered endemic in Uganda, the disease has been controlled effectively through conventional breeding.

CBSD is caused by two distinct viruses: cassava brown streak virus and the Ugandan cassava brown streak virus. CBSD is a complex disease as it causes different symptoms in different parts of the plant. In fact, one can observe no visible physical symptoms above the ground yet find root damage. Furthermore, CBSD does not seem to follow a predictable spread of dispersion, rather appears in isolated “hot spots” across the country, making it more difficult to monitor than other diseases. CBSD's complexity implies that economic and agronomic impacts are also difficult to measure. Documented impacts of CBSD includes yield reduction, tuber rot, and yield foregone for planting earlier to avoid the disease (Figure 4).

Figure 4. Documented CBSD impacts.



Source: Author's elaboration based on Gaffney et al. (2012), Alene et al. (2013).

The disease control response

The emergence of BXW in bananas and CBSD in cassava has introduced significant pressures on Uganda's top food security crops. These two diseases are quite complex and difficult to control using agronomic and cultural practices including host plant resistance introduced through conventional plant breeding and use of disease-free planting material produced using tissue culture.

Fortunately, progress has been made in recent years with significant advancement in genetic engineering R&D and in regulatory processes to enable the use of advanced biotechnology techniques. These techniques can contribute to the development of disease resistant banana and cassava varieties in Uganda (Kikulwe et al., 2013). Genetic engineering products has shown promise of being a better approach to other options as resistance seems to be effective and long term. Public policy questions are: First, what is the value of GE banana and Cassava to Uganda? Second, are observed R&D and regulatory advancements in Uganda conducive to an enabling environment to the deployment of new genetic engineering technologies to farmers? We pursue discussions of these two questions in the following sections.

The GE crop approach as an alternative

Investments in biotechnology development leading to the introduction of genetically engineered (GE) crops have been shown to have significant impacts on disease management, yield improvement, poverty reduction and food security (Ainembabazi et al., 2015). Moreover, Klümper & Qaim (2014) demonstrate remarkable economic impacts from GE crops such as significant reduction in pesticide use, yield gains and increased profits for farmers.

Genetically engineered cassava varieties that are resistant to CBSD (Sekabira *et al.*, 2018) and Banana Xanthomonas Wilt (BXW) resistant banana (Tripathi et al., 2017) are under development and are poised for introduction in Uganda. While the current policy debate in Uganda and in other countries has centered on the safety of GE crops, numerous questions regarding their economic viability and the potential economic impacts remain.

A sampling of questions and issues raised by partners in PBS-BioRAPP launching and planning events, as well as, consultations done with crop and GE developer experts, decision makers and other interested parties include: : (1) has the need to for regional differences in attributes and demands for the targeted cassava and banana varieties been considered in the development of the GE varieties; (2) will the incremental benefits be accrued as a result of adoption with focus on yield increases and losses averted; (3) what would be the farmers' associated costs including the risk of not adopting the technology; (4) what would be the potential commercialization pathway of these crop varieties; and (5) what would be the adoption rates and therefore impacts across different regions in Uganda; (6) what would be the economic impact of significant delays in releasing GE varieties? In this discussion paper, we provide initial analysis to help address these questions.

3. Background and Rationale for the Study

To support innovation that may help address pressing agricultural constraints in Uganda, decision makers need access to current and robust knowledge about potential impacts and trade offs. Experience has shown that access to robust knowledge supports better decision making. Considering critical problems for bananas and cassava, such as the CBSD and BXW diseases, and the potential technology interventions such as genetic engineering to address these constraints, an evidence-based approach to biosafety policy development and implementation is important to facilitate evaluation of new varieties and facilitate release of approved varieties to farmers. Evidence includes not only scientific evidence about safety and global best practices for legal and regulatory review, but evidence related to economic or social impact.

Economic and environmental questions are increasingly requiring a local evidence-based answer. Economic and environmental assessments may draw knowledge from international evaluations, but typically there is scant national evidence and low capacity to efficiently and timely respond to questions raised about local economic impact of new GE varieties, many of which are important food security crops, in development. The later situation is slowly changing. As Zambrano et al. (2019) has shown, there is growing body of literature focused on the economic assessment of GE crops in Africa. The nascent body of literature although still having a strong focus on insect resistance and herbicide tolerance in maize and cotton in South Africa, has indeed expanded to other crops, traits and countries. The Zambrano et al. (2019) paper indicates that up to 2016 there were 72 unique economic assessment papers meeting the selection criteria set by the authors of the compilation in the African context.

As stakeholders' questions are typically complex and the economic assessments difficult to communicate, outputs from such assessments are greatly improved if they are open, transparent, participatory by design and adherent to elements of best practice (Smale et al. 2008; Falck Zepeda and Gouse 2017). Furthermore, assessment of in country issues preferably should be country owned and implemented by local experts, using robust economic and environmental tools, guided by elements of best practice, subject to peer review and scrutiny. Due to decision makers demands and needs, such evaluations are preferably timely to address pressing questions supporting decision making and helping ensure stakeholder buy-in.

Ex ante assessments in bananas and cassava

Recent attempts have been made to estimate economic impacts from the adoption of GE crops. For instance, Sekabira et al. (2018) conducted an *ex ante* economic impact assessment for adoption of transgenic cassava varieties in East Africa and found out that adoption of biotechnology derived CBSD resistant varieties, would bear a net financial benefit of US$ 436 million in Kenya and US$ 790 million in Uganda over a period of 35 years.

Relatedly, Ainembabazi et al., (2015) performed an ex-ante economic impact assessment of genetically modified banana resistant to Xanthomonas Wilt in the Great Lakes Region of Africa. The results showed that the expected initial adoption rate ranges from 21 to

70 percent, while the ceiling adoption rate is up to 100 percent indicating that investment in the development of GE banana is economically viable. However, aggregate benefits vary substantially across the target countries ranging from US$ 20 million to 953 million. Benefits are highest in countries where disease incidence and production losses are high (losses ranged between 51 and 83 percent of production).

A study by Abele and Pillay (2007) estimated that an uncontrolled BXW infestation in Uganda at a rate of 8% per year translates to 2.1-4.5 million tons per year in a 10-year period and 56% maximum infestation level. Extrapolated to Uganda as whole, this translates to 2 billion US$ economic losses over a decade due to price and production impacts.

In this study, we perform an *ex ante* economic assessments of locally relevant GE technologies with focus on BXW resistant banana and CBSD resistant cassava. In contrast to previous studies described previously, we disaggregated Uganda to consider regional variations in supply and demand, adoption patters and other assumptions. Most important we carefully elicited assumption data from local experts and stakeholders, used a more structured economic model, while expanding the analysis to consider uncertainty and irreversibility. This will be an important step in providing timely, local, evidence-based estimations about the economic benefits of these new technologies while building the local capacity to conduct such studies independently.

4. Model and analytical approach

Several approaches have been used to evaluate the ex-ante socio-economic and environmental impact of agricultural technologies (Alston & Norton, 1995). These approaches include; Dynamic models such as Real Options analysis (Kikulwe et al., 2008; Savastano and Scandizzo,

2010) and Dynamic Research Evaluation for Management in Python (DREAMpy), a menu-driven software package for simulating a range of market, technology adoption, research spillover, and trade policy scenarios based on a flexible, multi-market, partial equilibrium model developed by IFPRI (DREAMpy 2020).

Other models and approaches include: Economic Surplus Model (ESM) (Ainembabazi et al., 2015), benefit-cost analysis (Rushton, 2009; Horstkotte-Wesseler et al. 2000), econometric models such as standard linear regression models (Muyanga, 2009), production function, cost function or an analysis of total factor productivity models (Fuglie 2018) and programming methods (Ouma, et al., 2004). The choice of the approach depends on trade-offs between acceptable assumptions including control for measurement error, general equilibrium effects, transaction costs and externalities (Ainembabazi et al., 2015).

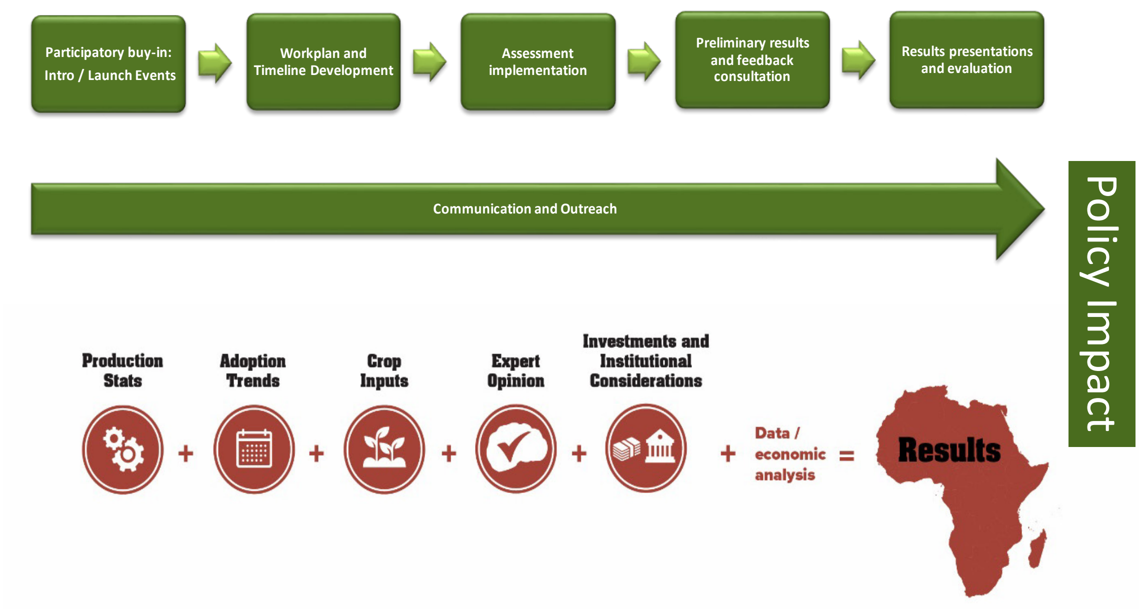
In this study, a multi-region Economic Surplus Model (ESM) implemented using IFPRI's DREAMpy and the Real Options approaches are used. The DREAMpy model allows for simulation and compares the benefits with and without the technology in single and multiple markets (Alston et al., 1995). This approach generates results for geographical locations as well as social groups within the area and changes in production patterns. The approach takes into consideration spillovers and the technology's adaptability (Babu & Rhoe, 2003).

Real Options theory developed by Mcdonald & Siegel, (1986), Dixit & Pindyck, (1994) and Schwartz and Trigeorgis (2004) focuses on the value of an option to invest under uncertain benefits (Trigeorgis & Tsekrekos, 2018). This allows for an investment decision involving real assets while providing for managerial flexibility in the valuation. Real options are based on multistage investments that require a decision at each stage. In other words, it facilitates modelling of uncertainty in both inputs and outputs (Scandizzo & Savastano, 2010).

Research process, data and assumptions

Figure 5 introduces a stylized description of the research process in Uganda implemented for the study described in this Discussion Paper. The process was led by a local, highly qualified and respected team of experts and with the participation of multiple collaborators from several institutions in the collection of secondary data, including production, prices, international trade, consumption and adoption trends.

Figure 5. Stylized description of the research process in Uganda



Source: BioRAPP 2018

Secondary data was collected at the regional level when available, while pursuing data triangulation using alternative sources. Local experts in a consultative manner conducted data cleaning and verification. Furthermore, local and international experts were consulted to identify assumptions used in the economic model. Public sector organizations and relevant ministries participated in guiding the study from its launch in Uganda via formation of a steering committee. The steering committee ensured access to locally relevant information, to provide country context and refine priorities and assumptions, as well as, to foster and secure ownership by Ugandan stakeholders. This process was supplemented by a transparent and on demand access to underlying data, assumptions, and the DREAMpy software and model use for estimations.

Data sources and assumptions

Bananas

Table 3 lists the basic static key parameters used in the economic surplus (ES) model as implemented in the DREAMpy approach for the BXW resistant banana. The main sources listed in the table represent the best available sources of secondary data and other information about banana cultivation in Uganda. As with other crops in low- and middle-income countries, there are several gaps in statistics about banana production in Uganda.

Where possible we have attempted to triangulate and compare these data with other sources of information and with individual studies. An example of the latter are the estimates of R&D and regulatory costs where variations are expected due to differences in estimation approaches. In the case of yield and cost changes, we used information collected by the Ugandan team with national and international banana crop experts and those from the technology developer community.

Table 3. Basic key parameters used in the ES estimation for the BXW resistant Banana in Uganda

Parameter	Unit	Assumption	Source/Note
Base year	Year	2015	Consultations with developers and stakeholders
Simulation period	Year	31	Adding up R&D, regulatory, and adoption lags; based on expert consultations
Real discount rate	Percentage	11	Ministry of Finance, Planning and Economic Development (Uganda, Ministry of Finance Planning and Economic Development. 2019)
Exchange rate	UGX/$US	3,246	Bank of Uganda (2018)
Price	1000 UGX /mt	346 -707	Varies by region, Uganda Bureau of Statistics (UBOS 2016)
Probability R&D & regulatory success	Percentage	80	Discussions with country experts
Extension, diffusion & product stewardship	Million UGX	5,030	Schieck et al. (2016) for late blight potato; Alene et al. (2018); unpublished estimates by Kikulwe (2019)
R&D costs	Million UGX	49,452	Schieck et al. (2016) for late blight potato; Alene et al. (2018); unpublished estimates by Kikulwe (2019)
Yield difference	Percentage	24 – 68	Survey with banana experts (values vary across regions)
Cost difference	Percentage	29 – 42	Survey with banana experts (values vary across regions)

Source: Authors' elaboration based on listed sources

Notes: Schieck et al. (2016) was consulted as it provides relatively detailed cost estimates for a vegetative plant. The data from Schieck helps construct cost estimates for the banana situation as some of the R&D activities in country are relatively similar. This is especially useful for extension, diffusion and product stewardship which are expected to be quite similar.

Table 4a shows the assumptions for the stochastic scenario estimations for BXW resistant banana including specific probability distributions used in DREAMpy. Assumptions used in the estimations were elicited via guidance questions answered by key crop and technology development experts[8] but also with additional small group expert discussions and personal interviews. In the case of supply and demand elasticities, we used those in IFPRI's IMPACT model, and other sources of information in the literature. As in the case of assumptions, we used variation across sources for inclusion in stochastic simulations.

For the stochastic simulations done in DREAMpy, minimum and maximum values for the probability distributions listed in Table 4a, correspond to the expected values for the pessimistic and optimistic scenarios across all regions. The only exceptions to this procedure are for the yield and cost changes probability distributions. As DREAMpy does not have the capability of entering probability distributions for the yield and cost changes individually, only for the K values, we manually estimated minimum and maximum values for the K probability distributions for each region by shocking the most likely value for yield and cost changes by +/- 20%. This approach yielded a set of minimum and maximum values which were slightly more conservative than what we obtained from expert opinion[9]. This approach was pursued in both the banana and with the cassava case below.

---

[8] Key banana and cassava experts where enlisted from the National Agricultural Research Organization (NARO) in Uganda and at the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) and other ministries. Key national and international technology development experts where enlisted from those research institutions currently in the R&D and regulatory pipeline. Key experts are all well recognized crop experts with a proven track record and experience in Uganda. These include Dr. Wilberforce Tushmereirwe, Dr. Titus Alicai, Dr. Anton Bua, Dr. Robert Kawuki, Dr. Henry Wagaba, Dr. Jerome Kubiriba, Dr. Kenneth Akankwasa and Dr. Walter Ocimati.

[9] We elicited most likely, maximum, and minimum values for yield and cost changes by region from experts. Expert opinion on most likely values is quite robust but experts had some reservations about maximum and minimum values. This is one area where more formal and systematic approaches to elicit expert opinion and group consensus will enhance the reliability of collected data.

Table 4b includes the most likely regional cost and yield assumptions used to estimate scenarios in the DREAMpy simulations. Expert opinion used to derive assumptions in Table 4b showed that the South-Western region not only has the lowest expected change in costs but also the lowest change in yield. As indicated before, the GM BXW resistant banana is not expected to have a larger impact in this region due to its specific production characteristics, the type of bananas planted and agronomic practices which have managed to maintain incidence at a lower level than in other regions.

Studies have shown that farmers in southwestern/western Uganda are less likely to adopt new crop varieties (Kasirye, 2013; Albertson, 2016) compared to other regions. Similarly, high volumes of production especially during surplus season coupled with higher transactions costs due to longer distances from the market affect the farm gate price significantly in southwestern Uganda, which in turn affect the expected producers' benefits. As discussed before, expected yield changes in SW Uganda resulting from technology adoption was estimated by scientists to be the least. The lower economic value of a BXW resistant GE banana may be due to many farmers in southwestern Uganda implementing the BXW control package most effectively than elsewhere during the previous BXW peaks and resurgence in 2014, while using better agronomic practices (including soil fertility and water conservation practices) than other regions (Kikulwe et al 2019; Katungi, 2007).

The introduction of a BXW resistant variety in southwestern Uganda may not result in much higher yields and may not change farmers' management of their plantations in presence (absence) of BXW significantly. Thus, lower expected yield changes, lower adoption rates, and lower farm gate prices greatly affected the potential benefits for producers in southwestern

Uganda compared to central and eastern Uganda. For example, the most case scenarios for adoption rates were estimated at 28% and farm gate prices at about UGX346,000/MT for southwestern Uganda compared to 55% and UGX491000/MT in central, respectively.

The observed cost changes are the net effect of increased seed cost and labor costs needed to replant coupled with a decrease in labor costs associated with the cultural practices needed to control BXW. The net effect is an overall cost decrease. Expected outcomes from the potential use of a BXW resistant banana will be examined in the results section.

Table 4a. Assumptions driving stochastic scenario estimation for the BXW resistant banana in Uganda

Variable	Minimum	Most Likely	Maximum	Distribution type	Source/Note
R&D and Regulatory lag	7	**9**	12	Triangular	Banana and crop development expert opinion
Adoption lag	7	**9**	12	Triangular	Banana and crop development expert opinion
K shift [a b]	92-225	**115 – 281**	138-225	PERT[c]	Banana and crop development expert opinion
Maximum adoption rate [a]	22-48	**28 – 61**	34=73	Triangular	Banana and crop development expert opinion
Elasticity of demand	-0.1	**-0.14**	-0.7	PERT	Robinson et al. 2015 Omamo et al. (2006), Chadwick and Nieuwoudt (1985)
Elasticity of supply	0.1	**0.266**	0.85	Triangular	Robinson et al. 2015, Komarek and Ahmadi-Esfahani (2011), Rudaheranwa et al. (2003)

Source: Authors' elaboration based on listed sources

Notes: [a] denotes values vary by region within range shown in table, [b] denotes most likely k-shift values based on yield and cost changes. For the stochastic simulations done in DREAMpy most likely values where shocked by +/-20%. PERT refers to a distribution used in the Program Evaluation and Review Technique developed for the US Navy to help their project analyses in the 1950s (Malcolm, Roseboom and Fazar, 1959). Probability distributions for minimum and maximum reflect the expected pessimistic and optimistic scenarios respectively.

Table 4b. Most likely cost and yield assumptions driving scenario estimation by region for the BXW resistant banana in Uganda[a]

Region	Change in Costs [b] (percent)	Change in Yield [c] (percent)
Eastern	42.4	68.0
Central	34.2	60.7
Mid-Western	37.1	53.3
South-Western	29.0	24.3
Northern	37.9	51.6

Source: Authors' elaboration

Notes: [a] k shift is estimated from change in costs and change in yield. [b] Denotes change in cost due to the use of the technology relative to total costs of production. Negative values imply a cost reduction compared to counterfactual. [c] Denotes values for yield changes between a BXW resistant and a susceptible variety.

Table 5 and 6a introduces key parameters used in the estimation of potential benefits from the introduction of CBSD resistant cassava in Uganda. Assumptions used in the modeling exercise are from best available secondary data sources in Uganda but also from those in the literature. Where possible we attempted to triangulate among different sources due to observed variations in data sources.

Table 6a introduces assumptions used in conjunction with key parameters in Table 5 to estimate economic surplus gains from the adoption of a CBSD resistant cassava. Assumptions were derived from secondary data and from a set of guidance questions answered by cassava crop experts and/or technology developers. Answers collected from individual cassava crop and technology development experts were complemented with small group discussions and personal interviews as in the banana case. As expected, there are several assumptions captured using probability distributions. As in the case of bananas, the source of elasticity of supply and demand values is from IFPRI's IMPACT model and other literature sources. Furthermore, discussion about probability distributions and most likely, minimum and maximum scenarios apply to cassava as described for the banana case above.

Table 5. Basic key parameters for CBSD resistant Cassava

Parameter	Unit	Assumption	Source/Note
Base year	Year	2015	Consultations cassava and technology development expert opinion
Simulation period	Year	31	Adding up R&D, regulatory, and adoption lags; based on cassava and technology development expert opinion
Real discount rate	Percentage	11	Ministry of Finance, Planning and Economic Development (Uganda, Ministry of Finance Planning and Economic Development, 2017)
Exchange rate	UGX/$US	3,246	Bank of Uganda
Price	1000 UGX / mt	223-306	Varies by region, Uganda Bureau of Statistics (UBOS)
Probability R&D & regulatory success	Percentage	70	Cassava and technology development expert opinion
Extension, diffusion & product stewardship	Million UGX	3,619	Schieck et al. (2016) for late blight potato; Alene et al. (2013 a2018); unpublished estimates by Kikulwe (2019)
R&D costs	Million UGX	4,664	Schieck et al. (2016) for late blight potato; Alene et al. (2018); unpublished estimates by Kikulwe (2019)
Yield difference	Percentage	25 Eastern & Central 17 Western 19 Northern	Cassava and technology development expert opinion; Alene et al. (2018); Ndyetabula et al. (2016) , National Cassava Program (2006)
Cost difference	Percentage	15 in all regions	Cassava and technology development expert opinion

Source: Authors' elaboration

Notes: Schieck et al. (2016) was consulted as it provides relatively detailed cost estimates for a vegetative plant. This helps construct cost estimates for the banana situation as some of the R&D activities but especially for extension, diffusion and product stewardship are expected to be quite similar.

Table 6a. Assumptions driving stochastic scenario estimation for CBSD resistant cassava in Uganda

Variable	Minimum	Most Likely	Maximum	Distribution type	Source/Note
R&D and Regulatory lag	6	**7**	10	Triangular	Survey with cassava experts
Adoption lag	3	**5**	12	Triangular	Survey with cassava experts
K shift [a b]	74.7 – 115.4	**93.4 - 144.2**	112.1-173.1	PERT	Survey with cassava experts
Maximum adoption rate [a]	55-60	**70-80**	75-85	Triangular	Survey with cassava experts
Elasticity of demand	-0.001	**-0.064**	-0.1	Triangular	Robinson et al. 2015, Takeshima (2008, 2011)
Elasticity of supply	0.1	**0.16**	0.85	Triangular	Robinson et al. 2015, Takeshima (2011)

Source: Authors' elaboration

Notes: [a] denotes values vary by region within range shown in table, [b] denotes most likely k-shift values based on yield and cost changes. For the stochastic simulations done in DREAMpy most likely values where shocked by +/- 20%. PERT refers to a distribution used in the Program Evaluation and Review Technique developed for the US Navy to help their project analyses in the 1950s (Malcolm, Roseboom and Fazar, 1959). Probability distributions for minimum and maximum reflect the expected pessimistic and optimistic scenarios respectively.

Table 6b. Most likely cost and yield assumptions driving scenario estimation by region for the CBSD resistant cassava in Uganda [a]

Region	Change in Costs [b] (percent)	Change in Yield [c] (percent)
Eastern	15.0	25
Central	15.0	25
Western	15.0	17
Northern	15.0	19

Source: Authors' elaboration

Notes: [a] k shift is estimated from change in costs and change in yield. [b] Denotes change in cost due to the use of the technology relative to total costs of production. Positive cost changes imply a cost increase compared to counterfactual. [c] Denotes values for yield changes between a BXW resistant and a susceptible variety.

Table 6b includes the most likely yield and cost change assumptions used in projections. In case of cassava, available data on key parameters was out of date or weak. There are several questions regarding cassava performance in Uganda which require data improvements to answer questions in a robust manner.

5. Results and Discussion

In this section we present the results obtained from various estimations. We first present main results from the stochastic Economic Surplus Model (i.e. DREAMpy model) and the Real Options Model.

DREAMpy model estimates

Bananas

Table 7 presents the change in total surplus from the potential adoption of a BXW resistant banana, which average US$ 25 million dollars per year over the 31 years of the simulation period. Values in bold in Table 7 are the most likely value from the DREAMpy stochastic simulation outcomes. The values directly underneath in parentheses are the 5th and 95th percentiles which constitute a confidence interval for stochastic economic surplus simulations as discussed in Davis and Espinoza (1998), Zhao et al. (2000) and Falck-Zepeda et al. (2000).

Total surplus gains per year varied among regions from US$ 0.2 million in Northern versus US$14.5 million in Central Uganda. Change in consumer surplus per year totals US$ 14.8 million. Change in consumer surplus per year varied from almost zero in Northern to US$ 6.3 million in Central. Change in producer surplus per year totals US$ 10.5 million. Change in producer surplus per year varied from a loss of US$ 4.2 million in South-Western to gain of US$ 8.2 million in Central. The negative outcome in South-Western results from the downward impact on prices from technology adoption which are not compensated by gains from technology use in the region.

Table 7. Change in average annual producer and consumer benefits and total net benefits for the BXW resistant banana in Uganda (million US$)

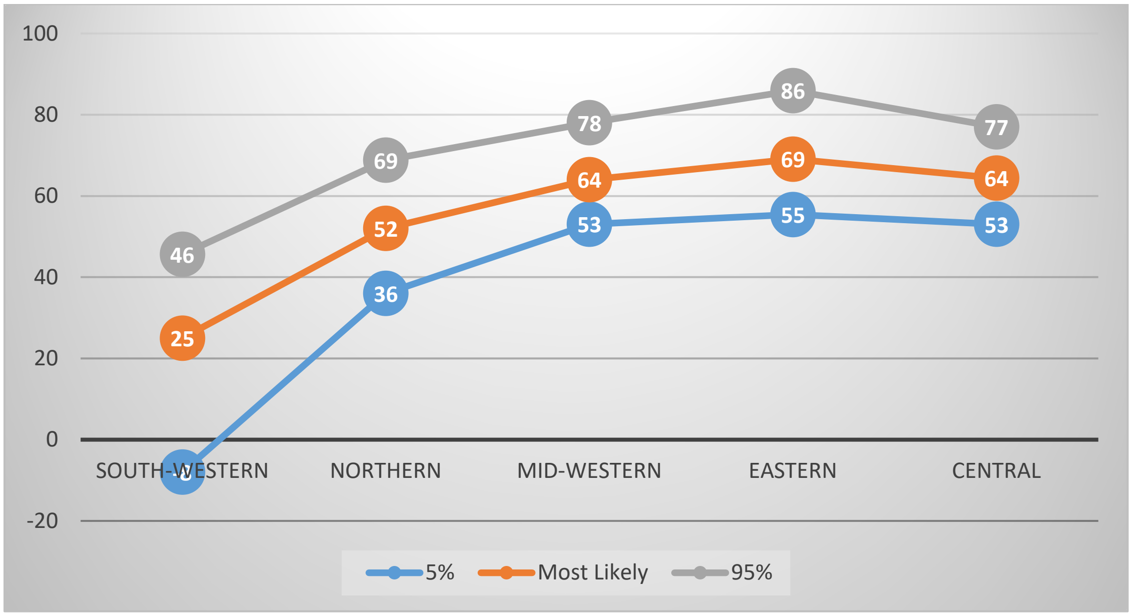
Region	Total ($)	Consumer	Producer
Central	**14.5**	**6.3**	**8.2**
	(10.1, 19.8)	*(4.0, 9.3)*	*(5.1, 11.8)*
Eastern	**4.5**	**1.2**	**3.3**
	(3.0, 6.3)	*(0.8, 1.8)*	*(1.9, 5.0)*
Mid-Western	**5.0**	**2.0**	**3.0**
	(3.7, 6.7)	*(1.3, 3.0)*	*(1.6, 4.7)*
Northern	**0.2**	**0.0**	**0.2**
	(0.1, 0.3)	*(0.0, 0.1)*	*(0.1, 0.3)*
South-Western	**0.8**	**5.2**	**-4.2**
	(-0.8, 2.4)	*(3.2, 7.8)*	*(-7.9, -1.4)*
Total Uganda	**25.0**	**14.8**	**10.5**
	(16.1, 35.5)	*(9.4, 21.9)*	*(0.7, 20.4)*

Source: Authors' elaboration

Notes: Numbers in bold are for the most likely scenario expressed in million US$ and are the average per year (number of years in simulation are n= 31 years). Numbers in parentheses and italics are the 5 percent/95 percent confidence interval corresponding to pessimistic and optimistic outcomes, respectively.

Figure 6 introduces estimates for the internal rate of return derived from the adoption of a BXW resistant banana in Uganda. Under the most likely scenario, internal rate of return varied by region, from 25 percent in Southwestern to 69 percent internal rate of return in Eastern. Interestingly, the possibility of having a negative IRR arises in the case of Southwestern. As can be seen in Figure 6, there is a 5 percent probability that the IRR is -8 percent or lower. Even with this unlikely scenario, it is indeed worthwhile to examine the determinants for this outcome. The need exists to examine structural issues related to technology adoption in general, but most importantly a potential release of a BXW resistant banana in Uganda especially in the Southwestern region.

Figure 6. Internal Rate of Return (percent) – BXW resistant banana in Uganda

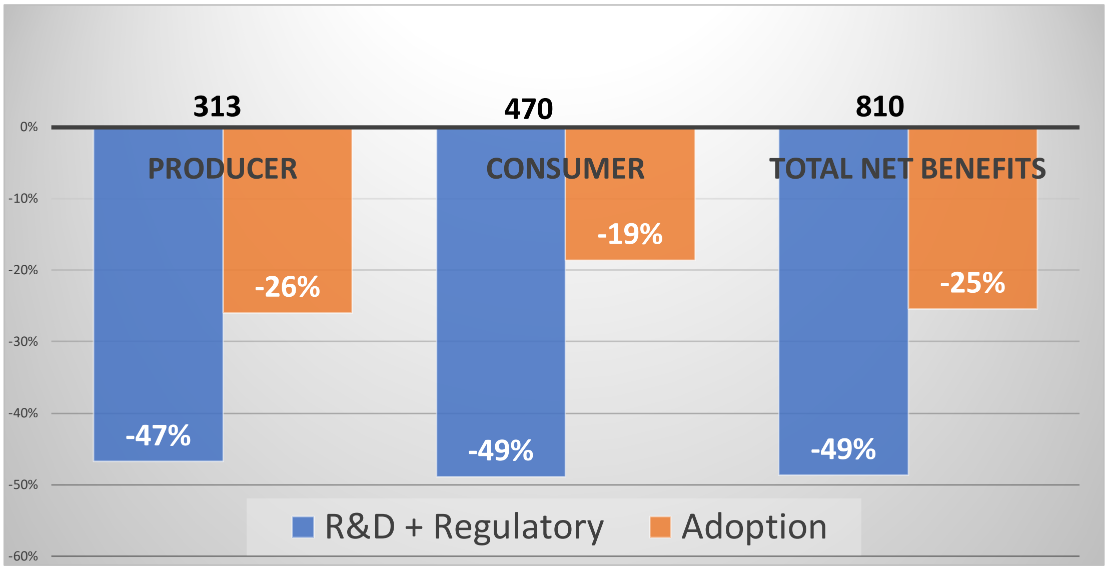


Source: Authors' elaboration based on DREAMpy results

Figure 7 describes the impact of R&D & regulatory and adoption delays on the release of a BXW resistant banana. R&D & regulatory delays refers to delay in the number of years it takes to complete both processes. R&D and regulatory processes may run concurrently and in practice cleanly separating both is not easy. For the purposes of this exercise we consider an increase in the number of years it takes to complete both. In DREAMpy this is referred to as "R&D time lag". We expand the R&D time lag in DREAMpy by 5 years, with the understanding that this refers to R&D and regulatory. Adoption lag refers to a delay in the number of years it takes to reach maximum adoption. In DREAMpy this is referred to as "Years to maximum adoption". We increased the number of years to maximum adoption by 5 years.

R&D and regulatory delays reduce potential benefits from the adoption of a BXW resistant banana by approximately 47-49 percent, whereas adoption delays reduce potential benefits by approximately 19-26 percent. Delays earlier in the life cycle of the potential technology tend to have a larger impact compared to those at later stages. Consequently, it is prudent to improve the efficiency of the R&D and regulatory processes as much as possible and decrease those delays, while recognizing and addressing credible concerns about the technology, its safety and performance.

Figure 7. BXW resistant banana – Impact of R&D, regulatory and adoption delays



Source: Authors' elaborations

Notes: Baseline values (313, 470 and 810) are in million US$ and are the total for the simulation period. Change values calculated from a modified baseline considering 36 years of simulation. This keeps the number of cash flows constant for baseline and the 5-year shocks. Estimation examines the pure time value of money. Based on DREAMpy results.

Cassava

Table 8 introduces the change in producer, consumer and total surplus from the introduction of CBSD resistant cassava in Uganda. Total benefits are an average of US$ 18.4 million per year over the 36 years of the simulation. These varied from US$ 1 million per year in the Western region to US$ 8.7 million in the Eastern region. In turn, producer surplus varied from a loss of US$ 1.1 million per year in the Western region to a gain of US$ 3.2 million per year in the Eastern region.

Producer losses per year in the Northern and Western regions are a consequence of gains achieved by using the technology not compensating additional costs and the downward pressures on prices from technology adoption. Additional efforts need to be paid in these two regions to ensure proper technology deployment but also to address more structural and value chain issues which may constrain production.

Table 8. Change in average annual producer and consumer benefits and total net benefits for the CBSD resistant cassava in Uganda (million US$)

Region	Total	Producer	Consumer
Central	**3.2** (2.3, 4.2)	**0.9** (0.0, 1.9)	**2.3** (1.8, 2.9)
Eastern	**8.7** (6.3, 11.5)	**3.2** (2.5, 5.3)	**5.6** (4.2, 7.1)
Northern	**5.4** *(4.0, 7.0)*	**-0.07** *(-1.3, 1.5)*	**5.5** *(4.2, 7.0)*
Western	**1.0** *(0.6, 1.5)*	**-1.1** *(-1.7, -0.5)*	**2.2** *(1.6, 2.8)*
Total Uganda	**18.4**	**2.9**	**15.5**

Source: Authors' elaboration

Notes: Numbers in bold are for the most likely scenario expressed in million US$ and are the average per year (number of years in simulation are n=31). Numbers in parentheses and italics are the 5th and 95th percentiles confidence interval corresponding to the pessimistic and the optimistic scenarios, respectively. Based on DREAMpy results.

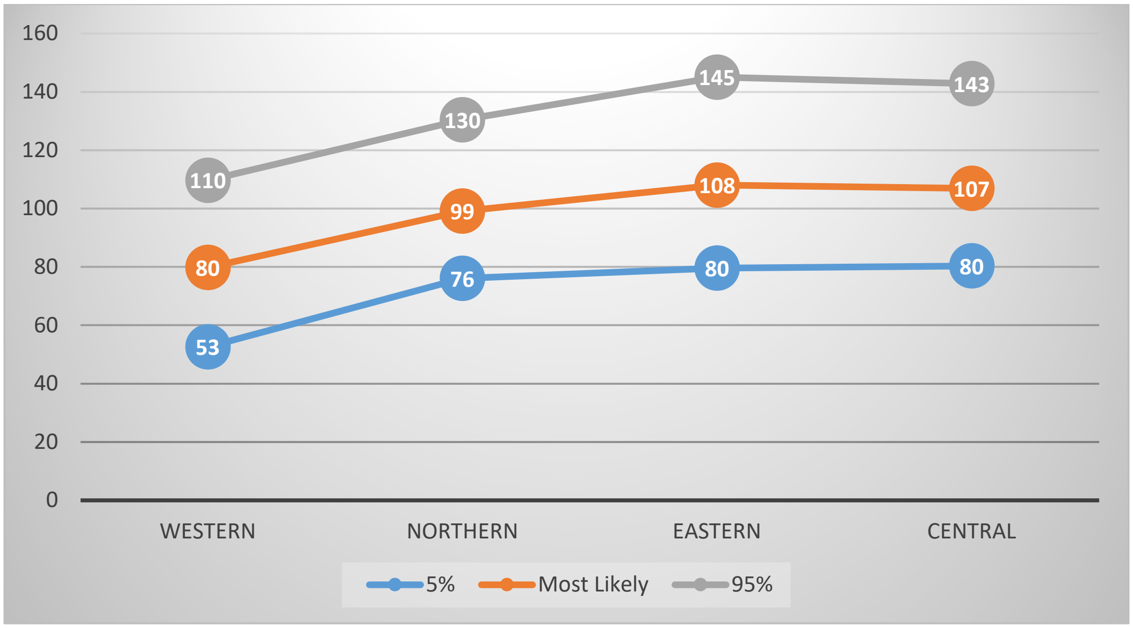
Figure 8 introduces the Internal Rate of Return by region from investments in a CBSD resistant cassava in Uganda. The most likely Internal Rate of Return varied from 80 percent in Western to 107 percent in Central. The most likely IRR results fall between the 5 percent and 95 percent boundaries in all regions. The outcomes for the 95th percentile for estimated IRR vary between 110 percent and 143 percent for Western and Central regions, respectively.

The 95th percentile in Table 8 may be interpreted as a ceiling for an optimistic set of outcomes, as there is a probability that 5 percent of outcome will be higher than the 95^{th} percentile values. In turn, the 5^{th} percentile for the estimated IRR varies is a floor ranging between 53 percent and 80 percent for Western and Central regions respectively. The 5^{th} percentile may be interpreted as a pessimistic set of outcomes as it is a ceiling for a set of outcomes, where there is a 5 percent probability that IRR may fall below the estimated IRR values in the 5^{th} percentile.

In all cases, the estimated IRR are positive and higher than the discount rate used in the estimation of the net present value. The decision-making rule is that an investment should be undertaken if the project's IRR is positive and is higher than the prevailing interest rate for investments. This signals that investments in R&D to derive a CBSD resistant cassava are a good investment for Uganda.

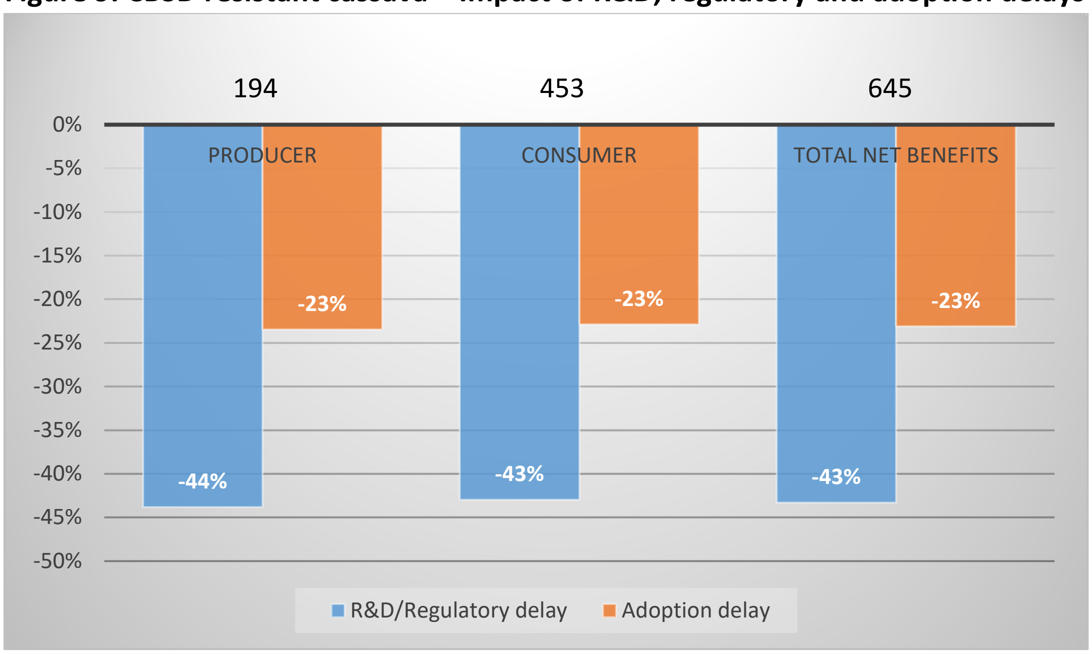
Figure 9 describes the impact of R&D, regulatory and adoption delays on the release of a CBSD resistant cassava. R&D and regulatory delays refer to those that occur before the commercial release of a technology. In turn, adoption delay refers to those that arise after the regulatory approval and during the technology transfer phase of the product's life cycle. R&D and regulatory delay may occur earlier than adoption delays.

Figure 8. Internal Rate of Return by region (percent) for CBSD resistant cassava in Uganda



Source: Authors' elaboration based on DREAMpy results

Figure 9. CBSD resistant cassava – Impact of R&D, regulatory and adoption delays



Source: Authors' estimations

Notes: Baseline values 194, 453 and 645) are in million US$ and are the total for the simulation period. Change values calculated from a modified baseline considering 36 years of simulation. This keeps the number of cash flows constant for baseline and the 5-year shocks. Estimation presented here examines the pure time value of money. Based on DREAMpy results.

To ensure that we are isolating the pure time value of money effect, we want to maintain a constant level of cash flows over the product's life cycle. This approach is correct assuming that a delay does not have an impact on the life span of the project. If delays do have an impact on the product's life cycle, then these effects should be properly described, and changes made to the number and type of cash flows over time. This issue will become relevant in the next section where we estimate the real options model, which considers the gains in additional knowledge over a time frame against cash flows losses. The difference is the contribution of additional knowledge that may be gained from additional testing and assessments.

R&D and regulatory delays reduce potential benefits from the adoption of a CBSD resistant cassava by approximately 43 percent, whereas adoption delays reduce potential benefits by approximately 23 percent. Delays earlier in the life cycle of the potential technology tend to have a larger impact compared to those later in the product's life cycle. In this sense, it is prudent to ensure improving the efficiency of the R&D and regulatory processes as much as possible and decrease those delays apart from those that may arise from credible questions about the technology and its safety and/or performance.

Real Option model estimates

In this section, we consider uncertainty, irreversibility and the flexibility to conduct technology investments in the evaluation of R&D and regulatory investments for cassava and bananas in Uganda. This section presents results based on two distinct measures derived from the Real Options literature: SIRBs (social incremental reversible benefits) and MISTICS (maximum incremental social tolerable irreversible costs). For a discussion of the Real Options approach see Annex 1.

Banana

Table 9 shows the estimated SIRBs for the BXW resistant banana in Uganda. Total SIRBS are US$ 88.3 million, whereas SIRBS per ha are US$ 292. SIRB net benefits vary significantly by region, from US$ 0.6 million in Northern, to US$ 23.0 million in South-western. Regions most affected areas by the BXW have the lowest SIRB per hectare.

Table 9. SIRBs for BXW resistant banana in Uganda

	Central	Eastern	Mid-Western	Northern	South-Western	Uganda
SIRB (million US$)	18	4	18	<1	23	88
SIRB per Ha (US$)	138	136	563	204	263	292

Source: Authors' estimations

Note: We used 11 percent discount rate and risk-free rate of return of 3 percent for the estimations.

Highest SIRBS are in the mid-western and south-western regions. Taking longer than necessary to complete the R&D and regulatory stages of a GE variety development may presumably result in failure to access the expected benefits from BXW resistant banana of US$ 88 million per year.

Table 10 introduces MISTICs estimates for the potential adoption of a BXW resistant banana in Uganda. MISTICs shows the maximum WTP for not having a BXW resistant banana. Average annual MISTICs per agricultural household are approximately US$ 21. An immediate release after the product is fully approved should be postponed only if the average agricultural household is willing to give up more than US$ 21 annually for not having BXW resistant bananas introduced.

The difference in MISTICs between banana growing and all agricultural households is large. This implies that banana growing households have a much larger interest than an average Ugandan agricultural household in having access to a BXW resistant banana even if a banana growing household is concerned about the irreversible costs. MISTICs values vary significantly across regions, with northern having the smallest value and south-western having the largest.

Table 10. MISTICs for BXW resistant banana in Uganda

	Central	Eastern	Mid-Western	Northern	South-Western	Uganda
MISTICs (Million US$)	17	4	17	<1	22	83
MISTICs per ha (US$)	130	128	531	192	248	275
MISTICs per agricultural household (US$)	21	3	33	<1	36	21
MISTICs per banana farm (US$)	83	54	129	16	63	106

Source: Authors' estimations

Note: Used 11 percent discount rate and risk-free rate of return of 3percent for the estimations

Cassava

Table 11 introduces results from the implementation of the real options model for the CBSD resistant cassava in Uganda. Average SIRB per year are US$ 141 million, which represents a total NPV benefit per hectare of US$ 2,269. Average benefits per hectare and year are US$ 272. Annual average benefits per household are US$ 36, whereas annual average benefits per farmer are US$ 114.

Table 11 also introduces MISTIC estimates for the potential adoption of the CBSD resistant cassava in Uganda. Average MISTICs per year are US$ 117 million. Average total NPV benefits per hectare adjusted by the hurdle rate are US$ 1,882 which represents average benefits per hectare and year of US$ 225. In turn annual average benefits per household are US$ 30, whereas annual average benefits per farmer are US$ 95. As a cross check, estimates from DREAMpy of producer surplus on average per household per year are US$39 whereas the average per farmer per year is US$ 123. These results are comparable to those in Table 9.

Table 11. Real Options Model results for the CBSD resistant cassava in Uganda

	SIRB	MISTICs
NPV (US$)	1,179,220,557	978,093,701
Average benefit per year (US$)	141,162,244	117,085,731
Total NPV benefit per ha (US$)	2,269	1,882
Average benefit per ha and year	272	225
Average per household/year	36	30
Average per farmer/year	114	95

Source: Authors' estimations

Note: Used 11 percent discount rate and risk-free rate of return of 3 percent for the estimations

Alternate Metrics

Economic surplus and real options are an estimation of income creation and efficiency. It is important to examine potential impacts on poverty alleviation and trade-offs between both goals. To examine such trade-offs, one can estimate changes in poverty status by using the Foster-Greer-Thorbecke (FGT) poverty indices as weights to economic surplus estimates (Moyo et al. 2007; Foster, Greer and Thorbecke 1984, 2010). Such inclusion allows the inclusion of poverty aversion levels to R&D decision making.

Annex 2 describes the process of including FGT class indices as weights to economic surplus estimates. Using total economic surplus estimates from Tables 7 and 8, we can estimate using the approach described in Annex 2 the number of poor escaping poverty on an annual basis based on the estimated average annual benefits from the adoption of the CBSD resistant cassava and the BXW resistant banana in Uganda.

Table 12. Estimates of the number of poor escaping poverty based on economic surplus estimates and the FGT class of poverty indices

Crop	Average annual benefit (billion US$)	Crop value of prod. (billion US$)	Average benefits as percent of ag prod.	Average benefits as percent of Crop's VOP	Poverty elasticity	Poverty reduction as percent of the poor	Number of poor escaping poverty
Bananas	0.025	0.60	0.53	4.18	0.72	0.4	54,766
Cassava	0.018	0.29	0.39	6.28	0.72	0.3	40,308

Source: Authors' estimations

Note: Based on 31 years of simulation and 14.3 million poor living in Uganda. Estimates based on Uganda having an agricultural value added of 4.7 billion US$.

Results in Table 12 show that average annual additional benefits estimates for bananas and cassava in Uganda accrue as projected, the equivalent number of people projected to escape poverty on an annual basis equals 54,766 for bananas and 40,308 for cassava. The estimates of the number of people escaping poverty from additional benefits resulting from the adoption of the BXW resistant banana and CBSD resistant cassava represent roughly 0.3-0.4 percent of the 14.3 million poor living in Uganda.

Gender considerations

Many countries in sub-Sahara Africa are characterized by low agricultural productivity. Improvements in productivity can lead to increased food security and improved livelihoods. The adoption of improved varieties is an important option to improve agriculture productivity (Minten & Barrett, 2008). Furthermore, women represent 50 percent or more of the agricultural labor force in Sub-Saharan Africa, yet they do not have equal access to assets, resources and knowledge that may contribute to their on-farm productivity (FAO, 2011).

The consequence of the access inequality is a gender productivity gap (Peterman et al., 2010; Quisumbing, 1996; De la O Campos et al., 2016) and it is not likely to be a result of differences in efficiency or management capacities (Quisumbing, 1996; FAO 2011). In addition, decision makers (men or women) may have different preferences and perceptions about technology, which, in conjunction with differential access, may lead to gender differences in adoption processes of improved practices and technologies (Meinzen-Dick, Kovarik and Quisumbing, 2014; Quisumbing & Maluccio, 2003). One impact of this situation is that men and women may adopt technologies at different rates.

Factors to consider in explaining adoption and productivity differences between men and women include land tenure, access to credit and inputs, labor availability, entitlements and decision-making power, access to extension services and membership in established member groups (Albertson, 2016; Fischer and Qaim, 2012; Meinzen-Dick et al., 2014). R&D processes and technology development may not be able to accommodate and drive specific technologies to meet the needs of all potential target users; a consideration of gender equity while mainstreaming gender factors will enhance the adoption and deployment of new agricultural technologies among women.

Considering the importance of gender access to improved varieties such as a GE banana or cassava, available data to estimate potential impacts disaggregated by gender is quite thin. Albertson (2016) found that neither gender nor household ownership was significant in explaining banana varieties adoption in Uganda. Yet, a district disaggregation of explanatory factors was significant, showing potential constraints for females to banana variety adoption. Kikulwe et al. (2018) show that gender and farmer perceptions about BXW are critical in explaining adoption of BXW control practices and for household food security. Addressing such perceptions in R&D and technology development processes is therefore critical reduce the gender gap in the adoption of new varieties and thus improve food security.

Considering Peterman et al. (2011) warning that traditional gender indicators could result in an underestimation of gender differences and the limitation of traditions surveys which do not consider gender issues starting from inception, we proceed to provide quite rough estimates of potential gender disaggregated impacts for bananas in Uganda. Our estimates are based on secondary data and quite thin -even heroic- assumptions about differences in gender-based performance. We conducted a limited exercise using the Real Options model for the case of bananas only, for which there is some available data (Bagamba et al. 2007; Albertson, 2016; Kikulwe et al., 2018).

There is no consistent gender disaggregated distribution of banana farmers in Uganda. Data from Bagamba et al. (2007) estimates that male farmers represent approximately 76 percent of total farmers as shown in Table 13. We can approximate area held by female and male farmers as in Table 13, although female households may be smaller in size. From Bagamba et al. (2007) and information in volume edited by Smale and Tushmereirwe (2007) female banana farmers in Uganda may not be as technically efficient as male farmers. These authors speculate that it may be due to access to assets and other constraints female farmers face producing bananas, as discussed above.

Nevertheless, for the purposes of this exercise we can assume that female farmers have lower yields than male farmers. Based on the area distribution by male and female farmers and the national average yield of 4.63 tons/ha (FAOSTAT, 2020), we can approximate male and female yields that will satisfy finding a weighted average from FAOSTAT data. Based on these assumptions, female farmers have an estimated yield of 2.8 tons/ha while male farmers 5.1 tons/ha as shown in Table 13. Assume that female farmers achieve 55 percent of the yield reached by male farmers. Furthermore, FAOSTAT (2020) which shows that in 2015 there where approximately 972,877 banana hectares in Uganda.

Table 13. Modified assumptions to examine gender differentiated impacts

Gender	Percent share	Number of hectares	Yield (tons/ha)	Production
Females	24	237,382	2.80	664,670
Males	76	739,387	5.10	3,770,873
	100			4,435,542

Source: Authors' compilation from Bagamba et al. 2007) and FAOSTAT (2020)

Using modified assumptions in Table 13, we re-estimate the real options model in Table 14 to disaggregate potential impacts of a BXW resistant banana. As expected, male farmers capture higher benefits measured as total and on a relative basis. Absolute numbers in Table 14 appear to be higher than the totals in Table 11. This has to do with the female/male proportions used in the estimation of Table 14. What is important from these results is the connection between yields, production and benefits.

Table 14. Gender-disaggregated estimates of economic impact

	Male		Female	
	SIRB	MISTICs	SIRB	MISTICs
Net Present Value (Mill. US$)	83	80	15	14
Average benefit per ha and year	318	306	170	164
Average per household/year	21	20	4	4
Average per farmer/year	139	134	76	74

Source: Authors' estimations

These estimates do not consider potential difference in the cost structure between female and male farmers, nor of any binding constraints that female farmers face especially for access to assets and other issues described in the introductory narrative. Nevertheless, these estimates in practice identify an urgent need to invest resources into efforts to gather proper gender sensitive data that will allow accurate and robust gender-disaggregated adoption impacts, but most importantly address the gender gaps and disparities described in Kikulwe et al. (2018) and Bagamba et al. (2007).

Gaps, Limitations and Opportunities

An important gap and qualifier for the outcomes estimated and described here is that statistics and data availability and quality, especially on yields, is problematic. This is particularly more limiting in the cassava case. In addition, epidemiology descriptors such incidence, prevalence and disease impact on yield, production and productivity are outdated or lacking for both BXW and CBSD in Uganda. Limited data availability of epidemiological, physical damage and disease/vector control measure effectiveness was a study limitation. Production budgets and disaggregated data by region are not readily available, especially for cassava. There is few gender-disaggregated data. Data that is available, is quite outdated.

Furthermore, the ES and real options models can be limited in addressing value chain estimations which may bias outcomes (See Takeshima 2008; 2011a and 2011b). In both cases, poor data availability on production and consumption especially region-based data, performance along the value chain and a limited understanding of economic roles especially in households, limits the analysis. Availability of gender disaggregated data for bananas and cassava, two important food security crops for Uganda, also limits any potential gender-disaggregated adoption impact estimates. As such, subsistence crop impacts may not be fully captured by the economic assessment models in the current discussion paper.

Despite these limitations, the use of DREAMpy and the real options models represent a pragmatic, data parsimonious and quite flexible approach to determine economic impact estimations. Gaps and limitations may be addressed within the models up to a point. Using stochastic simulations to address outcome sensitivity to input parameters is feasible and may yield estimates of potential variation to describe ongoing situation with bananas and cassava in Uganda. The ongoing situation with both crops raises opportunities to contribute to the policy dialogue in Uganda (see Annex 4 for an infographic used to communicate results from estimations described in this discussion paper.)

6. Policy Discussion

Uganda, as is the case with many African economies, has had slow deployment of new agricultural technologies supporting sustainable intensification systems that can provide food, fiber and raw materials for industrialization. Genetic engineering, one of the many tools employed in developed agricultural production systems, has contributed about USD 186 billion in farm income gains to producers' farmers in the first 20 years of commercialization of GE crops (ISAAA, 2018). GE research in Uganda has focused on addressing local production and nutrition constraints. Hence the efforts to manage bacterial wilt in banana and brown streak disease in cassava. Results from this study indicate that GE technology that addresses these specific challenges, is economically viable, and would result in direct overall benefits of USD 43.4 million each year, for a total of 31 years, to farmers and consumers once deployment hurdles are addressed. While the product development phase of the research is nearly complete, GE crops are unlikely to be deployed without an enabling regulatory environment.

Whereas the country's Legislature approved biosafety legislation twice in the past two years, the Executive's decision to withhold assent twice seems to suggest that political will may be the most limiting factor in further development of GE research in Uganda, and indeed in many African countries. Biosafety legislation has been mainly developed to provide a mechanism for safety review and decision making on GE products on a case by case basis. Recent discussions have expanded to include other considerations that have made the current version of the biosafety bill more difficult to implement if approved. Farmers, traders, processors, scientists, and investors alike would be affected by the proposed strict liability regimes, labeling requirements, and multiple certification requirements for each of stage of research, commercial release, trade, import, transit and export.

As revealed in this study, a five-year regulatory and research/development delay in the deployment of wilt resistant banana would reduce benefits by up to 49 percent. This translates into a loss of USD 500 million to the economy, a considerable value in Uganda's USD 26 billion (nominal GDP) economy. The lack of an enabling legal framework as well as a restrictive legal framework could both affect deployment of relevant GE crops in Uganda.

The government of Uganda is already supporting initiatives to add value and expand the industrial use of both banana and cassava. The Banana Industrial Research and Development Centre (formerly the Presidential Initiative on Banana Industrial Development) aims to optimize the use of all banana plant parts – fruit, leaves, stem – into competitive products such as gluten free starch, fabric, juices, and fermented products. Such efforts are unlikely to succeed until the BXW damage is adequately addressed in a sustainable manner. Experts warn that host plant resistance is the only reasonable long-term method to control this disease and a GE solution will be ready by 2023 if an enabling biosafety regulatory system is established.

Estimates from this study show that GE bacterial wilt resistant banana would protect up to 82 percent yield on farmers gardens, allowing producers to harvest and market more to support the government's industrialization and job creation initiatives. Efficient management of pests and diseases forms an important component in agricultural production, enabling efficiencies that would support national and global competitiveness.

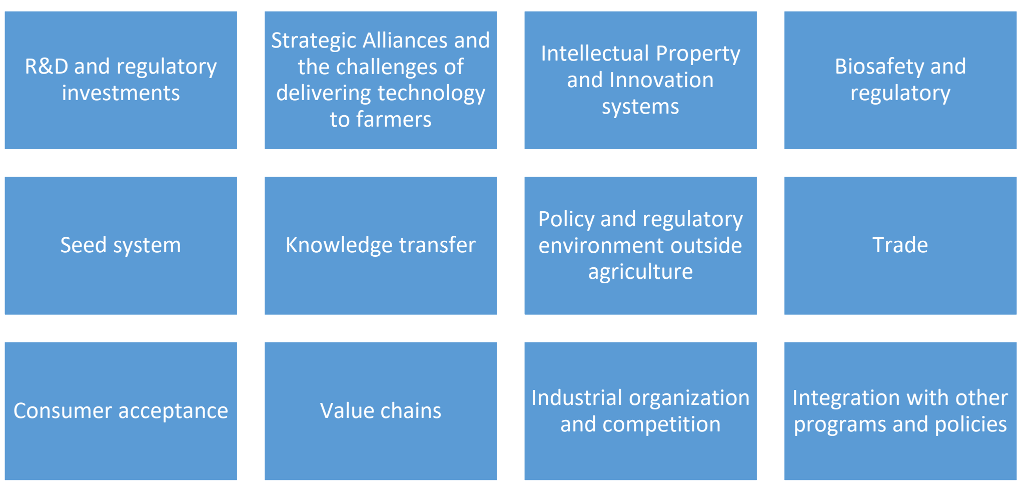
As already noted, without technological efficiencies in agricultural production, achieving desired quantities of raw materials for a sustainable agro-processing industry would be unrealistic. This therefore implies that managing crippling disease constraints such as BXW and CBSD must be priority policy intervention. This applies to food security considerations as well. Evidence from other economies show that countries have indeed adopted GE varieties of crops of strategic national value to their development. Brazil and Argentina adopted GE herbicide tolerant soybean to support their large export market for soybeans. India adopted GE insect resistant cotton to support the country's textile industry. Kenya's Cabinet recently approved the use of GE insect resistant cotton to support its job creation agenda by expanding the textile industry. Evidence from this study shows Uganda can also strategically benefit from deploying appropriate GE technologies, once biosafety considerations have been met.

The Uganda Government is further considering an ambitious Cassava Industrialization Program to add value, create employment opportunities and boost incomes of farmers in northern and eastern Uganda. The incidence and damage due to CBSD in these regions is very high, particularly in eastern Uganda. In stakeholder discussions of results from this study, government technical leaders expressed concern that management of CBSD should be an integral part of the industrialization program, as the disease continues to cause heavy losses to farmers. This study revealed that a five-year regulatory and R&D delay to deploy GE brown streak resistant cassava would cost the economy about USD 300 million. Cassava farmers lose an estimated USD 120 per ha every year due to this disease and the GE solution could ameliorate this loss and protect farmers' yield and provide the require quality raw material for the cassava industry.

As the country further contemplates its bioeconomy policy that is currently under development by the Ministry of Science, Technology and Innovation, agricultural biomass will be an important component of the strategy. Without appropriate technological interventions to address production and processing constraints for key staple and cash crops such as banana, cassava, maize, beans, soybean, and rice, the country is not expected to optimize the potential in these crops to drive the bioeconomy policy needed to support the country's Vision 2040. In the next National Development Plan (2020/21-2024/25), the country has prioritized agro-industrialization and job creation. Agriculture, as noted earlier, employs most people and workable strategies must be deployed to make the agro-sector productive, competitive and sustainable to support these ambitious plans. GE technologies coupled with good agronomic practices can contribute to enhancing productivity and sustainability. An enabling regulatory framework, and high-level political will, are essential to deployment of any GE crops in Uganda.

However, technology deployment does not occur in a vacuum, nor is it an isolated discrete event. GE technologies, as any other technology, are usually the result of purposeful national policies and laws that promote and/or hinder biotechnology and other innovations. A number of considerations will influence deployment of GE technology in crop agriculture as in Figure 10.

Figure 10 Issues to contemplate in a conducive governance and policy environment



Source: Based on Ruhinduka et al. (2019)

This study highlighted the economic evidence case for deployment of GE crops in Uganda using bacterial wilt resistance banana and brown streak disease resistant cassava as examples. The estimates can guide biosafety policy decisions and selected considerations identified by Furman, Porter and Stern (2002). Biotechnological solutions are different for each crop/trait combination and as such, issues such as IPRs, seed systems, consumer acceptance, and trade have to be considered on a case by case basis, and in many cases are not limiting factors in deployment of GE technology.

To summarize, Pixley et al. (2019) argues the likelihood that technological progress will continue is high but will be tempered by social and institutional factors expressed in policies and regulations in a specific country. Therefore, the policy context matter for the successful deployment of valuable technologies. As has been discussed in Ruhinduka et al. (2019) a conducive governance and policy environment helps deploy valuable technologies.

7. Summary and Conclusions

A GE BXW resistant banana can benefit Ugandan farmers and consumers. Average annual benefits are approximately US$ 25 million**,** of which producers receive US$15 million and consumers US$ 10 million. The average annual benefits per hectare are **US$293.** BXW resistant bananas adoption can have an impact on poverty. Average annual net benefits' gain from BXW adoption represents a **0.5 percent** share of Uganda's agricultural value added whereas net gains are equivalent to **55,000** poor people escaping poverty annually. Investing in BXW resistant bananas R&D is cost effective as the rate of return is 55 percent. R&D, regulatory and adoption delays have significant impact on outcomes. A 5-year delay during the research and regulatory process reduces the rate of return to 36 percent, whereas A 5-year delay during the adoption process reduces rate of return to 46 percent.

A CBSD resistant cassava can benefit Ugandan farmers and consumers. Average annual benefits are approximately US$18.4 million, whereas **US$2.9 million** for producers and **US$15.5 million** for consumers. Average annual benefit per hectare are **US$ 238.** CBSD resistant cassava adoption can have an impact on poverty. Average annual net benefits' gain from CBSD adoption represents a **0.12 percent** share of Uganda's agricultural value added. Net gains are the equivalent of 44,000 poor people escaping poverty, annually. Investing in CBSD resistant cassava R&D is also cost effective. Investment rate of return is 109 percent. As in the case of BXW resistant bananas, a five-year research and regulatory delay reduces this rate of return to 60 percent whereas a five-year adoption delay reduces this rate to 85 percent.

The benefits described in this paper depend significantly on the adoption, technology, market and economy wide assumptions used. There is the need to examine the institutional and organizational constraints that may hamper deployment of this and other technologies in Uganda that includes examining issues related to seed systems, intellectual property and seed registration, capacity to deploy new seed technologies, existence of indigenous business model to propel seed dissemination. Undertaking this assessment before release can help ensure both technologies success in addressing BXW and CBSD in Uganda. An enabling policy environment would be critical to deployment of these technologies in the country.

Annex 1 Description of models used in the Uganda case study

The Economic Surplus Model

The economic surplus model developed in Alston et al. (1995) is widely used to examine the research-induced economic surpluses generated in an output market. The model uses a system of supply and demand equations to model markets. Total economic surplus is distributed between producers and consumers. The model is widely used as it is relatively data parsimonious. Furthermore, the ES model is flexible in that it allows alternate market types, technology, adoption, spillovers, input costs and dynamics into the modeling process.

Alston et al. (1995, 53) detailed the main drawbacks of their proposed ESM approach: "ignoring transaction costs, externalities, general equilibrium effects and certain measurement errors", but clarify that most of these issues can be at least partially addressed by incorporating them into the estimated cost and benefits variables. Scatasta et al. (2006) add to this the fact that the ESM is very sensitive to changes in key assumptions, particularly elasticities, estimated changes in yield and input costs. Sensitivity to key assumptions can also be addressed through sensitivity analysis and/or by a more systematic approach such as the stochastic economic surplus approach (Falck Zepeda et al. 2000). Box 1 summarizes drawbacks to the use of economic surplus models. Despite these limitations, the economic surplus model is widely used to examine the distribution of benefits of new agricultural technologies and other technologies.

Box A.1 Summary economic drawbacks from ESM implementation

Alston et al. (1995), Smale et al. (2006) and Falck-Zepeda et al. (2008a and 2008b) point out some limitations of the economic surplus model:

- The economic surplus is calculated based on Marshallian demand that considers the effects of change in prices but ignores the effect of changes in income.
- The model assumes there are no transaction costs, and the markets clear and function well.
- This approach ignores general equilibrium effects by assuming that prices and quantities of other commodities produced by farmers are fixed.
- The model does not consider the effects on input markets.
- This model assumes farmers are risk-neutral and price-takers who either maximize profits or minimize costs.

The need exists to keep in mind all the drawbacks described previously when examining results from an economic surplus estimation, such as the ones in this paper. This allow proper result contextualization and policy interpretation. We present different scenarios to account for variability in key parameters and assume there are cost of extension. Additionally, by performing cross-checks with other related methodologies, we were able to test sensitivity to key parameters and assumptions through the stochastic economic surplus and the real options model. Of critical importance is the process pursued during project implementation where implementing team spent a substantial amount of time validating and documenting all data and assumptions used in the model.

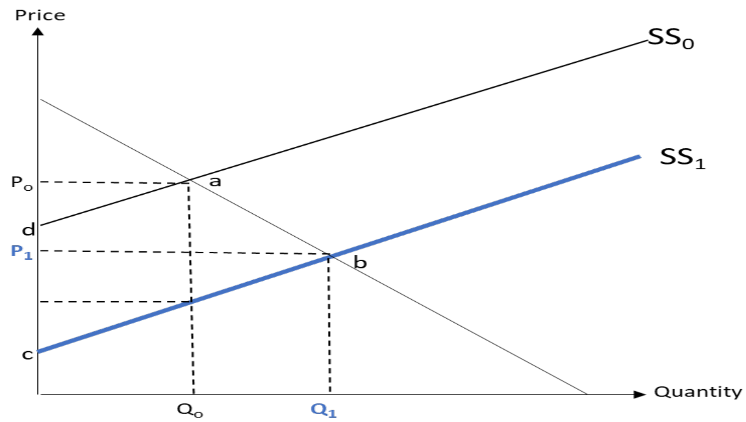
To better understand the ESM implemented we now proceed to a short description of the model[10]. A detailed description of the ESM implemented can be found in Alston et al.

---

[10]All estimations presented in this paper used the IFPRI- developed software DREAMpy (Dynamic Research Evaluation for Management in Python. A detailed theoretical presentation of DREAM ESM modeling, as well as all relevant documentation can be found in https://dataverse.harvard.edu/dataset.xhtml?persistentId=hdl:1902.1/18230

(1995). Here we introduce a basic ESM model to understand its elementary underpinnings. The introduction of a technology, in this case a GE technology, if effective, will enable producers to be able to decrease their unit cost of production via reduction in input use and/or induce a yield increase. This is reflected in the down and rightward shift of the supply curve from SS_o to SS_1, as depicted in Figure A1.A1.

Figure A1.1 Measuring welfare effects of a technology through the induced shift of the supply curve



Source: Authors' elaboration

The technology induced shift in the supply curve will result in a lower clearing price, moving the equilibrium price from P_o to P_1, with an increased in the quantity demanded from Q_o to Q_1. The net welfare effect of the technical change induced shift of the supply curve is measured as the change in consumer surplus (ΔCS) in addition to the change in producers' surplus (ΔPS). This is total surplus (ΔTS) which is represented by the area *abcd* in Figure 1

Following Alston et al. (1995) notation, the net welfare effect in a closed economy model can be estimated through a formula which uses variables including prices, quantities, elasticities and proportional changes in costs of production. The equations for consumer, producer and total surplus are:

Change in Consumers Surplus

$$\Delta CS = P_0 \, Q_0 \, Z \, (1 + 0.5 \, Z \, \eta) \qquad (1)$$

Change in Producers Surplus

$$\Delta \, PS = P_0 \, Q_0 (K - Z)(1 + 0.5 \, Z \, \eta) \qquad (2)$$

Change in Total Surplus

$$\Delta \, TS = \Delta \, CS + \Delta \, PS \qquad (3)$$

Where, Z = $K\varepsilon / (\varepsilon + \eta)$ is the price reduction due to the shift in the supply curve SS. *K* is specifically *the* vertical shift of the supply curve expressed as a proportion of the initial price P_0, and ε and η is the elasticity of supply and demand, respectively. *K* is calculated using the formula:

$$K = \left[\frac{\Delta Y}{\varepsilon_s} + \frac{\Delta C}{1 + \Delta Y}\right] \qquad (4)$$

Where ΔY= change in yield, ΔC= change in costs, ε_a is the elasticity of supply. Change in costs include those directly attributed to the technology and all other costs necessary to bring the technology to farmer's hands. These expressed as a share of total production costs. This basic approach is modified in DREAM to accommodate multi-region technology adoption with associated regional production characteristics.

The Stochastic Economic Surplus

One of the limitations of the economic surplus model is its inability to deal directly with sensitivity analysis of key parameters, uncertainty about values key parameters may take, and stochastic events that may be derived from values of such parameters. An alternative is to introduce probability distributions replacing static values of parameters in the economic surplus equations as proposed in Davis and Espinoza (1998), Zhao et al. (2000) and Falck-Zepeda et al.

(2000).

If we take the equations for the change in producer surplus (ΔPS) and the relative change in cost of production (K_{it}), for example, we can replace individual parameters such as P_0, Q_0, ε, η or actual changes in yields E(Y) or changes in costs E(C) with a probability distribution such as the triangular, normal, or the PERT distribution. A computer program can conduct a quasi-random sampling within each probability distribution and calculate values for outputs such as producer, consumer and/or total surplus as in the static case. This process of sampling and calculating values for outputs can be conducted as many times as the assessor deems necessary to gain a robust portfolio of outcomes. The computer program can calculate conventional statistics and measures of the output distribution which allows to know the probability of potential outputs based on the proposed model and its parameters.

DREAMpy has now the capacity to conduct stochastic simulations based on probability distributions for key parameters, and values are imputed in the chosen probability distributions. DREAMpy takes the imputed probability distributions, conducts quasi random sampling, computes designated outputs and estimates statistics across multiple iterations chosen by the assessor. In this paper, we chose to repeat this process 5,000 iterations which produced stable results across all iterations.

The Real Options Model

Investments in plant breeding techniques –including GE approaches– are a decision process under uncertainty, irreversibility and flexibility. Investors in GE technologies may not be able to assign probabilities to potential outcomes or processes (e.g. biosafety regulatory processes) and thus operate under uncertainty. Investors may have limited ability to adjust to changes in demand and supply for R&D products. R&D investors may need to make decisions about investing now in an R&D activity that will yield a GE technology in a 10-15-year time span from concept stage to commercialization, versus, waiting for the option –but not necessarily exercise the option– of learning and gathering more information about the technology. Finally, biotechnology impacts may generate irreversible costs and benefits from producer adoption.

Under these conditions a Real Options approach is preferable. The Real Options approach allows estimation of economic welfare by considering irreversible effects to see how the stream of incremental benefits will be affected in a longer planning horizon- in a continuous state and in continuous time. Meanwhile technologies may be private or public/external. The combination of these technology characteristics give rise to a matrix such as that in Table A1.1.

Table A1.1 Real options framework for irreversibility and type of good

	Private	External/public
Reversible	Q1 Private Reversible Benefits Private Reversible Costs	Q2 External Reversible Benefits External Reversible Costs
Irreversible	Q3 Private Irreversible Benefits Private Irreversible Costs	Q4 External Irreversible Benefits External Irreversible Costs

Source: Demont, Wesseler and Tollens (2004)

The real options model shows how much incremental benefits producers would forego due to increases in costs and/or with reductions and restrictions in technology deployment and the investment, stop or postpone decision while facing a regulatory process. A basic explanation of the real options approach is one where the decision making considers timing of investments and the corresponding benefits and costs flows over time.

A description of the Maximum Incremental Social Tolerable Irreversible Costs (MISTICs) approach to implementing a Real Options model used in this paper follows. The MISTICs approach followed in this discussion paper was proposed in Scatasta, Wesseler and Nillesen (2006), and Scatasta, Wesseler and Demont (2005). To pursue a tractable estimation approach, it is necessary to use a set of reasonable assumptions such that the assessor can estimate a hurdle rate. A hurdle rate is a parameter estimated from a time dataset (such as production values at the national level) that takes into consideration irreversibility, flexibility and uncertainty. The hurdle rate defined as $(\beta / (\beta - 1))$ is used to transform net benefits to discounted values and is estimated as follows:

$$\beta = \frac{1}{2} - \frac{r-\delta}{\sigma^2} + \sqrt{\left[\frac{r-\delta}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}} > 1 \qquad (5)$$

where δ is the difference between risk adjusted discount rate (μ) and α (drift rate), σ^2 is the variance rate, and r is the riskless interest rate. The parameters α (drift rate) and σ^2 (variance rate) can be estimated using time series data. It is important to estimate the Social Incremental Reversible Net-Benefits (or SIRBs), which can be based on producer surplus estimates derived from constant elasticity log-linear supply functions.

To consider irreversibility, the need exists to calculate the Social Incremental Irreversible Net Benefits (SIIBs) from reductions in pesticide or herbicide use. Because of issues of estimating benefits and as stakeholders seem to be concerned more about irreversible costs of the technology Scatasta, Wesseler, and Nillesen (2006), Scatasta, Wesseler and Demont (2005) proposed the use of the Maximum Incremental Social Tolerable Irreversible Costs (MISTICs). MISTICS are a threshold values that indicate the maximum incremental social irreversible costs that an individual or society in general is willing to tolerate for the sake of the benefits of the technology can provide useful information. If the real options is pursued, the new decision making rules using MISTICS is one where:

$$I^* = \frac{W}{\beta/_{(\beta-1)}} + R \qquad (6)$$

where, *I** is the Maximum Incremental Social Tolerable Irreversible Costs (MISTICs), *R* is the Social Incremental Irreversible Costs (SIIC), *W* is the Social Incremental Reversible Benefits (SIRB), and the Hurdle rate ($\beta/_{(\beta - 1)}$) captures the uncertainty and flexibility effect. The Real Options Decision Rule using estimated MISTICs can be interpreted as the maximum willingness to pay (WTP) for utilizing a technology now. Actual incremental irreversible social costs (*I*) are to be no greater than the sum of incremental irreversible social benefits and incremental reversible social net benefits for use of a plant breeding technique such that:

$$I < I^* = \frac{W}{\beta/_{(\beta-1)}} + R \qquad (7)$$

Annex 2 Translating changes in economic surplus into alternate metrics of poverty impacts

Moyo et al. (2007) proposed using the Foster, Greer Thorbecke (FGT) class of poverty index to translate gains estimated using the economic surplus methods to poverty impacts. The FGT index in Foster, Greer and Thorbecke (1984, 2010) is defined by the following equation:

$$P(\alpha) = \frac{1}{n}\sum_{i=1}^{q}\left[\frac{z-yi}{z}\right]^{\alpha} \qquad (1)$$

Where *n* is the total population, *q* is the number of poor individuals or households, those at or below income *z, yi* is income or expenditure of the *ith* poor individual or household, *z* is the poverty line and is measured in the same units as the is y, most applications use $1 or $2 per day (adjusted por purchasing power parity) as a metric α is a parameter of inequality aversion.

In the P(α) estimation, if the parameter of inequality aversion equals zero (α=0) then the P(α) becomes a measures of headcount ratio. The headcount ration is the fraction of the population that lives below the poverty line. The P (α) defaults to the following formula:

$$P\alpha = \frac{q}{n} \qquad (2)$$

If the parameter of inequality aversion equals 1 (α= 1) then the P (α) becomes the poverty headcount index times the poverty gap index. The average poverty gap is the amount of income necessary to bring everyone in poverty right up to the poverty line divided by total population. This can be thought of as the amount that an average person in the economy would have to contribute for poverty to be just barely eliminated. The formula for P (α)=1 is:

$$P\alpha = \frac{1}{n}\sum_{i=1}^{q}\left[\frac{z-yi}{z}\right] \qquad (3)$$

Higher α values considers higher weights to individuals with lower income. If Pα=2 then this becomes the squared poverty gap. In this form, the index combines information on both poverty and income inequality among the poor.

$$P\alpha = \frac{1}{n}\sum_{i=1}^{q}\left[\frac{z-yi}{z}\right]^2 \qquad (4)$$

The FGT class of indexes can be used to weight economic gains, such those from the economic surplus estimations, due to its additivity properties. Under additivity (or additive decomposability), the impacts of poverty change in a population can be assessed by adding up poverty changes in sub-groups where each subgroup is weighed by its population share (Foster, Green and Thorbecke 1984, 2010). Estimates from producer and consumer surplus can be weighed by the FGT index.

This is the approach followed by Alene et al. (2018). The authors proposed the following formula based on the FGT index to transform changes in economic surplus into change in the estimated change in the total number of poor moving above the poverty line as follows:

$$\Delta N_p = \left(\frac{\Delta ES}{AV}\ x\ 100\ \%\right)\ x\ \frac{\partial \ln\left(\frac{N_p}{N}\right)}{\partial \ln(Y)}\ x\ N_p \qquad (5)$$

Where N_p is the total number of poor, ΔN_p is the change in the number of poor potentially moving above the poverty line, ΔES is the change in economic surplus, AV is the agriculture value added, N is the total population, Y is agricultural productivity. The term $\frac{\partial \ln\left(\frac{N_p}{N}\right)}{\partial \ln(Y)}$ is the poverty elasticity relating the marginal impact of a 1 percent increase in agricultural productivity to the total number of poor. The term $\frac{\Delta ES}{AV}\ x\ 100 percent$ relates economic gains in terms of agricultural production.

Annex 3 Substantial expansion in Ugandan cassava production

The following is an estimation of the potential impact of substantial Ugandan cassava production expansion assuming the adoption of a CBSD resistant cassava. The purpose of this exercise is to highlight not only the value of expansion but also the value of a GE technology disseminated into a larger market area to support the Government of Uganda Cassava Industrialisation Program that is currently under discussion. This preliminary estimation is meant to be a primer to discuss the value of improving yields, reducing yield losses due to CBSD and other pathogens, but also to emphasize the need to examine the institutional, policy and regulatory issues that may be barriers or constraints to technology adoption. Such discussions before releasing the technology, can help reduce the possibility of technology failure due to such issues.

How to achieve a doubling in production?

As noted above, Uganda is producing less than 3 million metric tons of cassava. A doubling of cassava production to 5.6 million metric tons of cassava may be achieved by increasing area, yields or a combination of both area and yield. Table A3.2 introduces estimations examining changes in production due to changes in area, yield and both at the same time. Scenario 1 considers an expansion in area maintaining constant yield. Scenario 2. Considers an increase in average yields per region with no expansion in area. Scenario 3 considers the potential of increasing both area and yields at the same time. Scenario 1 and 2 would require either a duplication of area harvested and yields respectively. In turn, there may be many potential combinations that may yield production duplication. Here we maintain a roughly 41 percent increase in yields and in the area harvested. Note that the increased area is just slightly higher than reported area in 2017. Therefore, the objective to address would be to increase yields.

Table A3.1 Area and yield combinations that may enable a doubling in production

			Scenario 1. Expansion area with constant yield		Scenario 2. Increase in yield and no expansion in area		Scenario 3. Increase in area and yield		
Region	**Area harvested (average 2013-2015, ha)**	**Actual Yield (mt/ha)**	**Potential expansion of harvested area (ha)**	**Projected Production (1000mt)**	**Increased yield (mt/ha)**	**Projected Production (1000mt)**	**Potential expansion harvested area (ha)**	**Increased yield**	**Projected Production (1000mt)**
Eastern	334,768	3.11	669,537	2,083	6.2	2,083	473,429	4.4	2,082
Central	124,945	3.22	249,889	804	6.4	804	176,697	4.6	804
Western	128,406	3.36	256,812	864	6.7	864	181,591	4.8	864
Northern	263,881	3.66	527,761	1,929	7.3	1,929	373,180	5.2	1,929
Total	851,999	3.33	1,703,999	5,680		5,680	1,204,897		5,680

Source: Author's estimations

The damage/loss from CBSD

Data on damage loss from CBSD is unfortunately out of date and incomplete. A survey conducted by the National Cassava Programme in 2005 provided indications of the level of incidence in some districts in Uganda. Table A3.2 summarizes the districts where CBSD has been reported and the total area for those districts.

Table A3.2 Districts where CBSD has been reported in Uganda

Region	**Districts infection reported (percent)**	**Districts infection not reported (percent)**	**Area infection reported (hectares)**	**Area infection not reported (hectares)**
Central	48.9	51.1	61,113	63,832
Eastern	37.7	62.3	126,049	208,719
Northern	12.3	87.7	32,452	231,429
Western	9.6	90.4	12,339	116,066
Total	27.2	72.8	231,953	620,046

Source: NARO -NACRI 2005

We can use this information to estimate damage loss from CBSD if in those districts where CBSD has been reported, the average difference as reported by experts between a resistant GE and a susceptible cultivar will apply. The patterns reported in Table A3.3 seem to conform to current observations made by experts. Most of the damage from CBSD occurs in Central and Eastern regions, whereas Northern and Western regions observed limited but not trivial damage.

Estimations in Table A3.3 is a first and rough approximation to the type of estimates that may be possible if levels of incidence where known such as in the study by Ndyetabula et al. (2016). Table A3.4 uses information collected by the Uganda Cassava Programme in 2005 and current expert opinion to derive production loss and their value due to CBSD. Damage from CBSD varies from 0.84 to 1.15 metric tons per hectare in average. Production losses vary between 58 and 129 US$ per hectare, representing approximately US$27 million.

Table A3.3 Estimates of production losses and value due to CBSD in cassava in Uganda

Region	Yield not infected	Yield infected	Production losses	Production losses	Production losses	Production losses	Production losses	Production losses	Production losses
	mt	mt	mt	1000mt	UGX	1000UGX	US$	mt/ha	US$/ha
Central	3.8	2.7	69,688	69.7	22,812,144,768	22,812,145	7,027,771	1.14	115
Eastern	3.8	2.7	144,686	144.7	52,959,882,642	52,959,883	16,315,429	1.15	129
Northern	4.6	3.5	33,811	33.8	11,972,241,572	11,972,242	3,688,306	1.04	114
Western	4.1	3.3	10,382	10.4	2,322,913,886	2,322,914	715,624	0.84	58
Total	4.1	3.1	258,567	258.6	90,067,182,868	90,067,183	27,747,130	1.06	120

Source: Author's estimations

Estimates provided here are, as indicated before, a rough approximation based on existing data. This estimate contrasts with crop damage loss due to CBSD reported elsewhere. For example, Ndyetabula et al. (2016) reports that crop damage due to CBSD in Tanzania can be as high as 70 percent loss. Based on their estimations, Tanzanian losses could be greater than 860,000 mt, which is equivalent to US$51 million. To produce a better estimate of damage loss values due to CBSD, Uganda will need to compile more granular data on incidence of CBSD in the country.

The annual economic value of CBSD resistant cassava with significant expansion

The proper method to estimate gains from a significant expansion in production area is through an economic model that considers all sectors of the economy such as the computable general equilibrium models. Expansion in the area of production of cassava may be limited by land area dedicated to other crops and/or other uses. Furthermore, there may be inputs that may limit how much cassava may be able to grow. For example, labor and other physical inputs such as fertilizer and water.

The assumption of a significant expansion in production rests on the assumption that a market will exist that will be able to absorb additional production. In summary, the results presented here can only be understood as a first approximation to the potential value of cassava expansion in Uganda in a scenario where we allow an increase in production via an increase in yields and area, maintaining other factors constant (the *ceteris paribus* assumption).

To help address the current economic surplus model limitations, we created an additional region in Uganda that will absorb additional production. To improve the predictive capacity of this model, we modify the assumption of the price elasticity of demand in our original model to -0.91 for the industrial sector implying a more reactive sector to cassava prices as compared to a subsistence consumption base. This is partially based on the approach taken by Takeshima (2011a and 2011b). In a general equilibrium model, the industrial sector (as differentiated from the subsistence sector) may produce and consume cassava as part of the value chain. With additional information and research, it may be possible to improve our small open economy surplus model to one of a vertical market that considers market markups along the value chain.

Table A3.4 Economic Surplus estimates for an expansion of the cassava production in Uganda

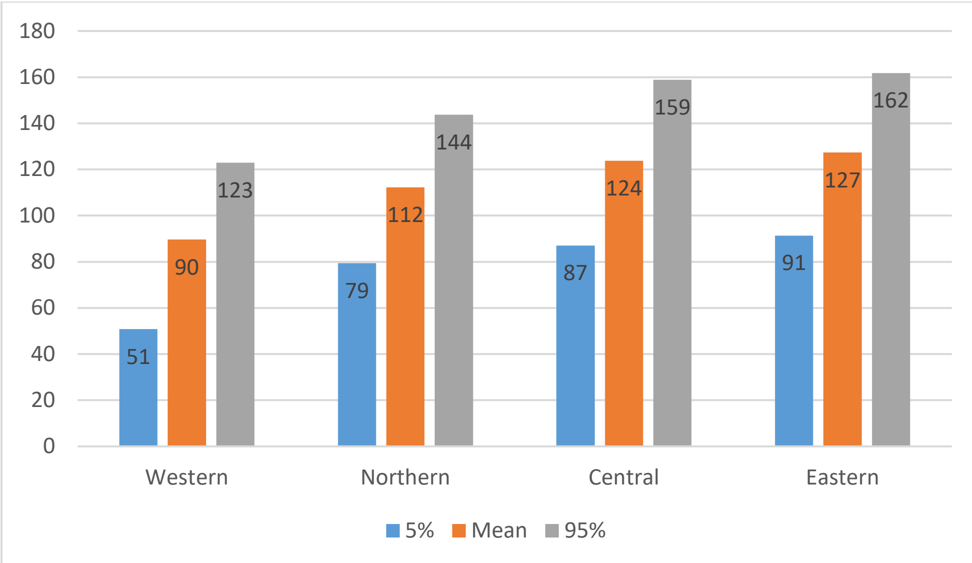
Region	Total Net Benefits	Producers	Consumers
Central	**5.1**	**4.0**	**1.2**
	(3.7, 5.8)	*(2.4, 4.6)*	*(0.8, 1.3)*
Eastern	**14.8**	**12.0**	**2.8**
	(10.9, 16.6)	*(8.3, 13.6)*	*(2.0, 3.2)*
Northern	**7.9**	**5.1**	**2.8**
	(5.7, 8.8)	*(2.7, 6.1)*	*(2.0, 3.1)*
Western	**1.5**	**0.4**	**1.1**
	(0.9, 1.7)	*(-0.5, 0.7)*	*(0.8, 1.2)*
Industrial sector	**6.1**	**-**	**6.1**
	(3.9, 7.0)	*(0.0, 0.0)*	*(3.9, 7.0)*
Total	**35.5**	**21.5**	**14.0**

Source: Author's own estimations

Notes: Numbers in bold are for the most likely scenario expressed in million US$ and are the average per year (number of years in simulation are n=31). Numbers in parentheses and italics are the 5th and 95th percentiles confidence interval corresponding to the pessimistic and the optimistic scenarios, respectively.

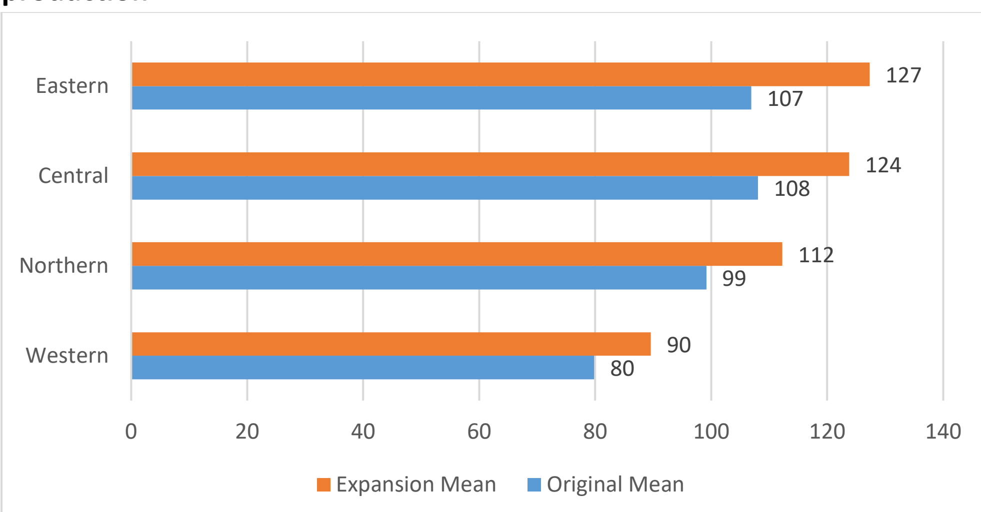
When comparing able A3.5 and Table 6, with a doubling of production total returns increase by approximately 60 percent without including benefits from the "industrial sector". The largest share of increase in total returns comes from an increase in producer benefits. As the development costs for a CBSD resistant cassava are spread over a larger production base and increased production, the internal rate of return increases with an expansion in cassava production (Figure A3.1 and Figure A3.2). This is an example of economies of scale.

Figure A3.1 Internal Rate of Return from an Expansion in Cassava Yield and Area



Source: Author's estimations

Figure A3.2 Comparison in the mean Internal Rate of Return (IRR) for baseline and expanded production



Source: Author's estimations

The industrial potential of cassava

Assessing the industrial potential customarily entails a mix of economic and institutional/organizational assessments. Although the institutional/organization assessment is not within the scope of the current assessment, it is important to describe briefly and to understand the context in which a CBSD resistant cassava will be deployed.

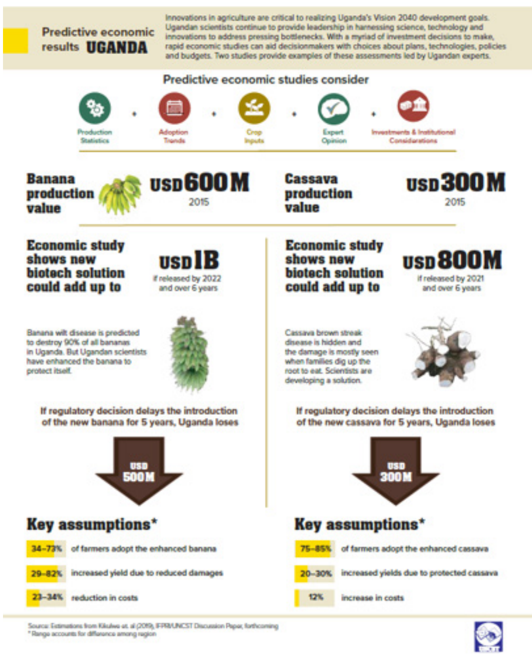
Potential expansion can be viewed as a portfolio of policies. From efforts to support overall area planted/harvested and yields, to specific project that can take limited areas and increase significantly yields and productivity. Calculations done in the previous section are of the former, whereas projects proposals such as that of AgriTT publications below are of the later.

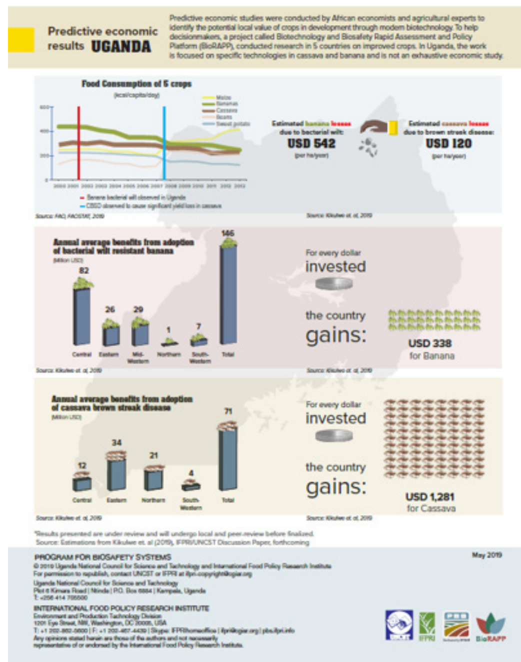
The AgriTT project proposal (http://knowledgeshare.sainonline.org/wp-content/uploads/2017/04/Potential-for-industrialising-cassava.pdf) considers two distinct types of expansion. One is a medium intensity focused on high quality cassava flour and starch production on 1,324 ha producing at 20 tons per hectare. This project option involves an investment of US$1.6 million and an annual return of US$ 832,400. The second option is an expanded approach where there is a significant expansion from the high-quality cassava flour and starch to glucose production that may have limited export potential. This option implies land expansion to 13,500 hectares producing at 20 tons per hectare and an investment of US$ 27.7 million.

Regardless of the approach pursued there are significant productivity constraints that will need to be addressed. As discussed in this discussion paper, addressing the issue of viral infestations due to CBSD and CMD in cassava will be necessary but not enough to guarantee increases in production and productivity. As discussed in a joint publication by NARO/NACRI/NOW/OXFAM and other Uganda organizations (see https://cng-cdn.oxfam.org/uganda.oxfam.org/s3fs-public/file_attachments/Opportunitiespercent20forpercent20Investmentpercent20inpercent20Cassava.pdf) there are multiple industrialization potential for further cassava transformation from high quality cassava flour and material for brewing to bioethanol and high quality planting materials. As discussed in the publication there are institutional issues that will need to be addressed to support such expansion not only for additional production, but also on productive inputs that support such production such as dryers and planting material. Institutional issues listed in Figure 7 will need to be addressed, along those related to R&D, regulatory and technology deployment issues discussed in the text, to help ensure the success of appropriate technology deployment and expansion success.

Annex 4 Infographic

Results for the optimistic scenario for the BXW resistant banana and the CBSD resistant cassava in Uganda summarized in an infographic, are shown below.





The optimistic scenario described in this report differ from those presented in this infographic published May 2019, before this report was finalized and reviewed. For clarity purposes, the optimistic scenario in the infographic above was selected from a single deterministic run of DREAMpy which used the parameter values likely to draw a higher output. In turn, results presented in this Discussion Paper are the result of multiple iterations using probability distributions. Runs from the multiple iterations yield in turn a distribution of outcomes defined by the distribution statistics including most likely and the 5th and 95th

percentiles. The likelihood of any single iteration outcome is quite low, thus the probability of obtaining the optimistic outcome as in the infographic, a value higher than the 95^{th} percentile value in the discussion paper, is also quite low. The probability of obtaining a value higher than the 95^{th} percentile value is less than 5 percent.

Another important annotation is that the information presented in the infographic above was customized to specific audiences in close consultation with country stakeholders. The values presented in the infographic represent the sum total of the R&D and regulatory costs incurred in country in addition to the first 6 years of cash flows after adoption starts in Uganda. As in any net present value calculation the further one goes in time, the net present value of each additional year’s cash flow decreases over time. Furthermore, earlier cash are discounted less. In the case of Uganda, with an 11 percent discount rate and 31 years of simulation, the cash flows in the first six year represent 48 percent of the total net present value accumulated over the life of the simulation.

References

Abaca, A., R. Kawuki, P. Tukamuhabwa, Y. Baguma, A. Pariyo, T. Alicai, C.A. Omongo and A. Bua. 2012. “Evaluation of Local and Elite Cassava Genotypes for Resistance to Cassava Brown Streak Disease in Uganda.” *Journal of Agronomy* 11 (3): 65-72.

Abele, S. and M. Pillay. 2007. “Bacterial Wilt and Drought Stresses in Banana Production and their Impact on Economic Welfare in Uganda: Implications for Banana Research in East African Highlands.” *Journal of Crop Improvement*, 19 (1-2): 173–14. doi:10.1300/J411v19n01_09.

Ainembabazi J. H., L. Tripathi, J. Rusike, T. Abdoulaye and V. Manyong. 2015. “Ex-Ante Economic Impact Assessment of Genetically Modified Banana Resistant to Xanthomonas Wilt in the Great Lakes Region of Africa.” *PLoS ONE* 10 (9):e0138998. doi:10.1371/journal.pone.0138998

Albertson, E. 2016. "Adopting new banana varieties in Uganda: the role of gender and head of household status." International Development, Community and Environment (IDCE). 27. https://commons.clarku.edu/idce_masters_papers/27

Alene, A.D., T. Abdoulaye, J. Rusike, R. Labarta, B. Creamer, M. del Río, et al. 2018. “Identifying Crop Research Priorities Based on Potential Economic and Poverty Reduction Impacts: The Case of Cassava in Africa, Asia, and Latin America.” *PLoS ONE* 13(8): e0201803. https://doi.org/10.1371/journal.pone.0201803

Alene, A.D., R. Khataza, C. Chibwana, P. Ntawuruhunga, and C. Moyo. 2013. Economic impacts of cassava research and extension in Malawi and Zambia. *Journal of Development and Agricultural Economics* 5 (11): 457-469.

Alicai, T., A. M. Szyniszewska, C. A. Omongo, 2019. “Expansion of the cassava brown streak pandemic in Uganda revealed by annual field survey data for 2004 to 2017.” *Scientific Data* 6 (327 2019). https://doi.org/10.1038/s41597-019-0334-9

Alston, J. M., G. W. Norton, and P. G. Pardey. 1995. *Science under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting.* Ithaca, NY, and London: Cornell University Press.

Alicai, T., A. Omongo, M. N. Maruthi, R. J. Hillocks, Y. Baguma, R. Kawuki, A. Bua, G. W. Otim-Nape, and J. Colvin. 2007. “Re-emergence of Cassava Brown Streak Disease in Uganda.” *Plant Disease* 91 (1): 24-29

Babu, S. C. and V. D. Rhoe. 2003. Assessing Agricultural Biotechnology: Applications of Ex-ante and Ex-post Methods to Genetically Modified Crops. Asian Biotechnology Development Review. 5 (3): 1-22.

BioRAPP. 2018. Predictive Economic Assessments at The Biotechnology and Biosafety Rapid Assessment Policy Platform (BioRAPP). Presented at the Uganda BioRAPP Steering Committee Meeting, May 2018, Kampala Uganda.

Bagamba, F., R. Ruben, and M. C. Rufino. 2007. Determinants of Banana Productivity and Technical Efficiency in Uganda. In *An Economic Assessment of Banana Genetic Improvement and Innovation in the Lake Victoria Region of Uganda and Tanzania*, edited by M. Smale and W. K. Tushemereirwe, 109-128, IFPRI Research Report 155, Washington, DC: International Food Policy Research Institute.

Bank of Uganda. 2018*. State of the Economy Report March 2018*. Kampala Uganda.

Blomme G., K. Jacobsen, W. Ocimati, F. Beed, J. Ntamwira, and C. Sivirihauma, F. Ssekiwoko, V. Nakato, J. Kubiriba, L.Tripathi, W. Tinzaara, F. Mbolela, L. Lutete and E. Karamura. 2014. "Fine-tuning banana Xanthomonas wilt control options over the past decade in East and Central Africa." *European Journal of Plant Pathology.* 139: 271-287.

Chadwick, J. B. and L. W. Nieuwoudt. 1985. "The Demand for Bananas and the Economic Effect of Supply Restriction." *Agrekon* 24 (2): 16-20. http://doi.org/10.1080/03031853.1985.9524046

Chambers, J. A., P. Zambrano, J. B. Falck-Zepeda, G. P. Gruère, D. Sengupta and K. Hokanson. 2014. GM agricultural technologies for Africa: A state of affairs. Washington DC: International Food Policy Research Institute and African Development Bank. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/128215

Danielsen, S., E. Boa, M. Mafabi, E. Mutebi, R. Reeder, F. Kabeere, and R. Karyeija. 2013. "Using Plant Clinic Registers to Assess the Quality of Diagnoses and Advice Given to Farmers: A Case Study from Uganda." *Journal of Agricultural Education and* Extension 19 (2): 183-201.

Davis, G. and M. Espinoza. 1998. "A Unified Approach to Sensitivity Analysis in Equilibrium Displacement Models." *American Journal of Agricultural Economics* 80 (4): 868–79.

De La O Campos, A., K. Covarrubias, and A. Patron. 2016. "How Does the Choice of the Gender Indicator Affect the Analysis of Gender Differences in Agricultural Productivity? Evidence from Uganda." *World Development* 77: 17-33.

Demont, M., J. Wesseler, and E. Tollens. 2004. "Biodiversity versus Transgenic Sugar Beet: The One Euro Question." *European Review of Agricultural Economics* 31 (1): 1–18.

Dixit, R. K. and R. S. Pindyck. 1994. Investment under Uncertainty. Princeton NJ: Princeton University Press, 488 pp.

DREAMpy. 2020. DREAMpy - Dynamic Research Evaluation for Management python version 2.2. Download at https://www.dreampy.org/

Falck-Zepeda, J. B., G. Traxler and R. G. Nelson. 2000. "Surplus Distribution from the Introduction of a Biotechnology Innovation *American Journal of Agricultural Economics.* 82:360-369.

Falck-Zepeda, J., J. Yorobe, B. A. Husin, A. Manalo, E. M. Lokollo, G. Ramon, P. Zambrano, and Sutrisno. 2012. Estimates and implications of the costs of compliance with biosafety regulations in developing countries. *GM Crops and Food: Biotechnology in Agriculture and the Food Chain*, Vol. 3 (1): 1–8

Falck-Zepeda, J. B., D. Horna, and M. Smale. 2008a. Betting on cotton: "Potential Payoffs and Economic Risks of Adopting Transgenic Cotton in West Africa. *African Jouranl of Agricultrual and Resource Economics* 2 (2): 188-207.

Falck Zepeda, J. B., D. Horna, P. Zambrano, and M. Smale. 2008b. Policy and Institutional Factors and the Distribution of Economic Benefits and Risk from the Adoption of Insect Resistant (Bt) Cotton in West Africa. *Asian Biotechnology Development Review* 11 (1): 1-32.

Falck-Zepeda, J.B. and M. Gouse. 2017. Regulation of GMOs in developing countries – why socioeconomic considerations matter for decision making. In *Genetically modified organisms in developing countries: Risk analysis and governance*, edited by A. A. Adenle, E. J. Morris and D. J. Murphy, 91 - 102. Cambridge, U.K.: Cambridge University Press.

FAO (Food and Agriculture Organization of the United Nations). 2011. *The State of Food and Agriculture 2010-2011 Women in Agriculture: Closing the Gender Gap for Development* Accessed March 1, 2020. http://www.fao.org/docrep/013/i2050e/i2050e00.htm

FAO (Food and Agriculture Organization of the United Nations). 2020. FAOSTAT Food balance sheet. Accessed March 19, 2020. http://www.fao.org/faostat/en/#data/FBS

FAO (Food and Agriculture Organization of the United Nations). 2020. FAOSTAT. Accessed January 17, 2020. http://www.fao.org/faostat/en/

Feed the Future. 2018. *Global food security strategy (GFSS) Uganda country plan.* Washington, DC: US Agency for International Development.

Feleke, S., V. Manyong, T. Abdoulaye, and A. D. Alene. 2016. Assessing the impacts of cassava technology on poverty reduction in Africa." *Studies in Agricultural Economics* 118 (2016) 101-111.

Fischer, E. and M. Qaim. 2012. "Gender, agricultural commercialization, and collective action in Kenya." *Food Security* 4 (3): 441–453. https://doi.org/10.1007/s12571-012-0199-7

Foster, D.A. and R. M. Rosenzweig. 2010. *Microeconomics of Technology Adoption*. Economic Growth Center Discussion Paper No. 984, New Haven, CT: Yale University.

Foster, J., J. Greer and E. Thorbecke. 1984. "A Class of Decomposable Poverty Measures." *Econometrica* 52 (3): 761–766. doi:10.2307/1913475. JSTOR 1913475.

Foster, J., J. Greer, and E. Thorbecke. 2010. "The Foster–Greer–Thorbecke (FGT) poverty measures: 25 years later". *The Journal of Economic Inequality* 8 (4): 491–524. doi:10.1007/s10888-010-9136-1

Fuglie, K. 2018. "R&D Capital, R&D Spillovers, and Productivity Growth in World Agriculture" *Applied Economic Perspectives and Policy* 40 (3): 421–444. https://doi.org/10.1093/aepp/ppx045

Furman, J. L., M. E. Porter and S. Stern. 2002. "The Determinants of National Innovative Capacity." *Research Policy* 31 (6): 899–933.

Gaffney, A., C. Kpaka, E. Slakie, E. and C. L. Anderson. 2012. *Cassava Integrated Value Chain* Evans School of Public Affairs EPAR Brief No. 223. Seattle, WA: University of Washington.

Geberewold, A. Z. 2019. "Review on impact of banana bacterial wilt (Xhantomonas campestris pv. Musacerum) in East and Central Africa." *Cogent Food & Agriculture* 5 (1): 1586075. https://doi.org/10.1080/23311932.2019.1586075

Gladwin, C. H., J. S. Peterson, D. Phiri, R. Uttaro. 2002. "Agroforestry Adoption Decisions, Structural Adjustment and Gender in Africa. In *Natural resources management in African agriculture: Understanding and improving current practices*, Edited by Barrett, C. B., Place, F., Aboud, A. A., 115-128. https://doig.org/10.1079/9780851995847.0115

Global Yield Gap and Water Productivity Atlas. Available URL: www.yieldgap.org (accessed on August 20, 2018)

Horstkotte-Wesseler, G., M. Maredia, D. Byerlee, and G. Alex. 2000. "Ex Ante Economic Analysis in AKIS Projects : Methods and Guidelines for Good Practice." *Agricultural Knowledge and Information Systems (AKIS) good practice note*. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/16183

ISAAA (International Service for the Acquisition of Agri-biotech Applications). 2016. *Global Status of Commercialized Biotech/GM Crops: 2016*. ISAAA Brief No. 52. Ithaca, NY: ISAAA.

ISAAA (International Service for the Acquisition of Agri-biotech Applications). 2018. *Global Status of Commercialized Biotech/GM Crops in 2018.* ISAAA Brief 54. Ithaca, NY: ISAAA.

Kagezi, G. H., A. Kangire, W. Tushemereirwe, F. Bagamba, F., E. Kikulwe, J. Muhangi, C. S. Gold, and P. E. Ragama. 2006. "Banana Bacterial Wilt Incidence in Uganda." *African Crop Science Journal* 14 (2): 83-91.

Karamura, E., G. Kayobyo, W. K. Tushemereirwe, S. Benin, G. Blomme, S. E. Green, and R. Markham. 2010. Assessing the Impacts of Banana Bacterial Wilt Disease on Banana (Musa spp.) Productivity and Livelihoods of Ugandan Farm Households. *Acta Horticulturae* 879: 749–756. https://doi.org/10.17660/ActaHortic.2010.879.81

Kasirye, E. 2013. Constraints to Agricultural Technology Adoption in Uganda: Evidence from the 2005/06-2009/10 Uganda National Panel Survey. RESEARCH SERIES No. 102, Economic Policy Research Centre (EPRC), Kampala, Uganda. http://dspace.mak.ac.ug/bitstream/handle/10570/4000/series102.pdf?sequence=1&isAllowed=y

Katungi, E.M. 2007. Social Capital and Technology Adoption on Small Farms: The Case of Banana Production Technology in Uganda. Thesis, submitted In partial fulfilment of the requirements for the Degree of Doctor of Philosophy (Agricultural Economics) in the Department of Agricultural Economics, Extension and Rural development Faculty Of Natural and Agricultural Sciences, University of Pretoria, South Africa

Kikulwe. E. M. 2019. Estimates of cost of compliance bananas. Unpublished, Bioversity International, Kampala Uganda.

Kikulwe, E.M., J. L. Kyanjo, E Kato, et al. 2019. Management of Banana Xanthomonas Wilt: Evidence from Impact of Adoption of Cultural Control Practices in Uganda. *Sustainability,* 11, 2610. https://doi.org/10.3390/su11092610

Kikulwe, E.M., S. Okurut, S. Ajambo, E. Gotor, R. Tendo Ssali, J. Kubiriba and E. Karamura. 2018. Does Gender Matter in Effective Management of Plant Disease Epidemics? Insights From a Survey Among Rural Banana Farming Households in Uganda. *Journal of Development and Agricultural Economics* 10 (3): 87-98. https://doi.org/10.5897/JDAE2017.0877

Komarek, A. M. and F. Z. Ahmadi-Esfahani. 2011. Impacts of price and productivity changes on banana-growing households in Uganda. *Agricultural Economics* 42 (s1): 141–151. http://doi.org/10.1111/j.1574-0862.2011.00558.x

Komarek, A. M. and F. Z. Ahmadi-Esfahani. 2012. “The impact of changing marketing conditions on Ugandan banana farmers.” *Journal of Agribusiness in Developing and Emerging Economies* 2 (1): 74–88. http://doi.org/10.1108/20440831211219246

Kubiriba, J., E. B. Karamura, W. Jogo, W. K. Tushemereirwe, and W. Tinzaara. 2012. “Community Mobilization: A Key to Effective Control of Banana Xanthomonas Wilt.” *Journal of Development and Agricultural Economics* 4 (5): 125-131.

Legg, J.P., S. C. Jeremiah, H. M. Obiero, M. N. Maruthi, I. Ndyetabula, G. Okao-Okuja, H. Bouwmeester, S. Bigirimana, W. Tata-Hangy, G. Gashaka, G. Mkamilo, T. Alicai, and P. Lava Kumar. 2011. “Comparing the regional epidemiology of the Cassava mosaic and Cassava brown streak virus pandemics in Africa.” Virus Research. 159 (2): 161–170.

Malcolm, D. G., J. H. Roseboom, C. E. Clark, W. Fazar. 1959. "Application of a Technique for Research and Development Program Evaluation," *Operations Research* 7 (5): 646–669.

Mcdonald, R. L. and D. R. Siegel. 1986. “The Value of Waiting to Invest.” *Quarterly Journal of Economics* 101 (4): 707-27.

Meinzen-Dick, R., C. Kovarik, and A. R. Quisumbing. 2014. “Gender and Sustainability.” *Annual Review of Environment and Resources* 39 (1): 29–55. https://doi.org/10.1146/annurev-environ-101813-013240

Minten, B. and C. B. Barrett. 2008. Agricultural Technology, Productivity and Poverty in Madagascar. *World Development* 36 (5): 797-822.

Moyo, S., G. W. Norton, J. Alwang, I. Rhinehart, C. M. Deom. 2007. “Peanut Research and Poverty Reduction: Impacts of Variety Improvement to Control Peanut Viruses in Uganda.” American Journal of Agricultural Economics 89 (2): 448 – 460. https://doi.org/10.1111/j.1467-8276.2007.00991.x

Muhangi, J., C. Nankinga, C., W. K. Tushemereirwe, M. Rutherford, P. E. Ragama, K. Nowakunda, and S. Abeyasekera. 2006. “Impact of Awareness Campaigns for Banana Bacterial Wilt in Uganda.” *African Crop Science Journal* 14 (2): 175-183.

Mware, B.O., E. M. Ateka, J. M. Songa, R. D. Narla, F. Olubayo, and R. Amata. 2009. "Transmission and distribution of cassava brown streak virus disease in cassava growing areas of Kenya." *Journal of Applied Biosciences.* 16: 864–870.

Okao-Okuja G, S. Hamba, J. Omara, E. Nuwamanya, R. Kawuki and T. Alicai. 2017. Cassava Baseline Survey Report 2017 – Cassava Applied Research for Food and Income Security in Northern Uganda Project. Kampala, Uganda: National Crops Resources Research Institute - National Agricultural Research Organization. https://knowledge4food.net/wp-content/uploads/2017/11/arf2-3d_uganda-cassava-baseline-report.pdf

National Cassava Program 2006. *Occurrence of Cassava Brown Streak Diseases in Uganda – Project A1150.* Kampala, Uganda: Namulonge Agricultural and Animal Production Research Institute - National Agricultural Research Organization.

National Development Plan II (NDPII) 2015/16-2019/20. Uganda Vision 2040 "A Transformed Ugandan Society from a Peasant to a Modern and Prosperous Country within 30 years." Kampala: National Planning Authority. http://npa.ug/wp-content/uploads/NDPII-Final.pdf

Ngambeki, D., W. K. Tushemereirwe and O. Okaasai. 2006. "Awareness of Banana Bacterial Wilt Control in Uganda: Community Leaders Perspectives." *African Crop Science Journal* 14 (2): 165-174.

Ndyetabula, I. L., S. M. Merumba, S. C. Jeremiah, S. Kasele, G. S. Mkamilo, F. M. Kagimbo, and J. P. Legg. 2016. "Analysis of Interactions between Cassava Brown Streak Disease Symptom Types Facilitates the Determination of Varietal Responses and Yield Losses." *Plant Disease* 100 (7): 1388–1396. http://doi.org/10.1094/PDIS-11-15-1274-RE.

Nyombi, K. 2013. "Towards Sustainable Highland Banana Production in Uganda: Opportunities and Challenges." *African Journal of Food, Agriculture, Nutrition and Development* 13(2):7544

Ocimati W., H. Bouwmeester , J. C. J. Groot, P. Tittonell, D. Brown, and G. Blomme. 2019. The Risk Posed by Xanthomonas Wilt Disease of Banana: Mapping of Disease Hotspots, Fronts and Vulnerable Landscapes. *PLoS ONE* 14 (4): e0213691. https://doi.org/10.1371/journal.pone.0213691

Ocimati W., G. V. Nakato, K. M. Fiaboe, F. Beed, and G. Blomme. 2014. "Incomplete Systemic Movement of Xanthomonas Campestris pv. Musacearum and the Occurrence of Latent Infections in Xanthomonas Wilt-Infected Banana Mats." *Plant Pathology* 64 (1): 81-90.

Okao-Okuja G, S. Hamba, J. Omara, E. Nuwamanya, R. Kawuki and T. Alicai. 2017. *Cassava Baseline Survey Report 2017 – Cassava Applied Research for Food and Income Security in Northern Uganda Project.* Kampala, Uganda: National Crops Resources Research Institute - National Agricultural Research Organization. https://knowledge4food.net/wp-content/uploads/2017/11/arf2-3d_uganda-cassava-baseline-report.pdf

Omamo, S. W., X. Diao, S. Wood, J. Chamberlin, L. You, S. Benin, U. Wood-Sichra, and A. Tatwangire. 2006. *Strategic priorities for agricultural development in Eastern and Central Africa*. IFPRI Research Report 150, Washington, DC: International Food Policy Research Institute. http://dx.doi.org/10.2499/9780896291584RR150

Otim-Nape, G. W., A. Bua, G. Ssemakula, G. Acola, Y. Baguma, S. Ogwal, R. Van der Grift. 2005. Cassava Development in Uganda – A Country Case Study Towards A Glboal Cassava Development Strategy." In *A review of cassava in Africa with country case studies on Nigeria, Ghana, the United Republic of Tanzania, Uganda and Benin* – Proceedings of the Validation Forum on the Global Cassava Development Strategy Volume 2, *International Fund for Agricultural Development and the Food and Agriculture Organization of the United Nations, Rome: Italy.*

Peterman, A., A. Quisumbing, J. Behrman, and E. Nkonya. 2010. Understanding gender differences in agricultural productivity in Uganda and Nigeria. IFPRI Discussion Paper 1003. Washington, DC: International Food Policy Research Institute.

Pixley, K.V., J. B. Falck-Zepeda, K. E. Giller, L. L. Glenna, F. Gould, C. A. Mallory-Smith, D. M. Stelly, and C. N. Stewart. 2019. Genome Editing, Gene Drives, and Synthetic Biology: Will They Contribute to Disease-Resistant Crops, and Who Will Benefit?. *Annual Review of Phytopathology* 57 (8): 8.24

Quisumbing, A. R. and J. A. Maluccio, J. A. 2003. "Resources at marriage and intrahousehold allocation: Evidence from Bangladesh, Ethiopia, Indonesia, and South Africa." *Oxford Bulletin of Economics and Statistics* 65 (3): 283-327.

Quisumbing, A. R. 1996. Male-Female Differences in Agricultural Productivity: Methodological Issues and Empirical Evidence. *World Development* 24 (10): 1579-1595.

Rudaheranwa, N., L. Bategeka, M. Banga, and A. Mukungu. 2003. *Supply Response of Selected Commodities in Uganda*. EPRC Research Series 36. Kampala, Uganda: Makerere University Economic Policy Research Centre.

Ruhinduka, R. D., J. B. Falck-Zepeda, U. Wood-Sichra, P. Zambrano, H. Semboja, J. Chambers, H. Hanson, and G. Lesseri. 2020. Ex Ante Economic Assessment of Impacts of GM Maize and Cassava on Producers and Consumers in Tanzania. IFPRI Discussion Paper 01911. Washington DC: International Food Policy Research Policy.

Rushton, J. 2009. *The Economics of Animal Health and Production.* CAB International, Oxfordshire & Massachusetts (2009), pp. 193-197.

Savastano, S. and P. L. Scandizzo. 2010. *The Adoption and Diffusion of GM Crops in USA: A Real Option Approach.* CEIS Tor Vergata Research Paper 169, Rome Italy: CEIS University of Tor Vergata. https://ssrn.com/abstract=1653915

Scatasta, S., J. Wesseler, and M. Demont. 2006. Irreversibility, Uncertainty, and the Adoption of Transgenic Crops: Experiences from Applications to HT sugar beet, HT corn, and Bt Corn. In *Regulating Agricultural Biotechnology: Economics and Policy,* edited by Just, R. E., Alston, J.M., Zilberman, D., 327-352. Boston, MA, USA: Springer.

Scatasta, S., J. Wesseler, and E. Nillesen, E. 2006. “Real Option and the Adoption of Transgenic Crops: An Intertemporal Perspective.” Paper presented at the 10th International Consortium on Agricultural Biotechnology Research (ICABR), Ravello, Italy, June 29 – July 2.

Schwartz, E. S. and L. Trigeorgis. 2004. Real Options and Investment under Uncertainty - Classical Readings and Recent Contributions. Cambridge MA and London UK: MIT Press, 881 pp.

Schiek, B., G. Hareau, Y. Baguma, A. Medakker, D. Douches, F. Shotkoski, and M. Ghislain. 2016. “Demystification of GM crop costs: Releasing late blight resistant potato varieties as public goods in developing countries.” *International Journal of Biotechnology*. 14 (2): 112–131.

Sekabira H., C. Sebatta, K. W. Sibiko, A. Bua, N. Taylor and C. Fauquet. 2018. “An Ex-Ante Economic Impact Assessment for Adoption of Varieties in Uganda and Kenya.” Advance in Nutrition and Food Science. ANAFS-101. Extracted online from: https://kosmospublishers.com/an-ex-ante-economic-impact-assessment-for-adoption-of-transgenic-cassava-varieties-in-uganda-and-kenya/.

Sherman, R. D. Mason D’Croz, S. Islam, T. B. Sulser, R. D. Robertson, T. Zhu, A. Gueneu, G. Pitois, M. W. Rosegrant. 2015. *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3.* IFPRI Discussion Paper 01483. Washington DC: International Food Policy Research Institute. https://www.ifpri.org/publication/international-model-policy-analysis-agricultural-commodities-and-trade-impact-model-0

Simoes, A. J. G. and C.A. Hidalgo. 2011. The Economic Complexity Observatory: An Analytical Tool for Understanding the Dynamics of Economic Development. Workshops at the Twenty-Fifth AAAI Conference on Artificial Intelligence. Extracted online January 2020: https://oec.world/en/

Slakie, E., C. McKee, A. Gaffney, C. L. Anderson and M. K. Gugerty. 2013. *Control Strategies for Whitefly as a Vector for Cassava Viral Diseases*. Evans School Policy Analysis and Research EPAR Brief No. 233. Seattle, WA, US: University of Washington.

Smale, M., and W. K. Tushemereirwe, eds. 2007. *An economic assessment of banana genetic improvement and innovation in the Lake Victoria Region of Uganda and Tanzania*. IFPRI Research Report 155. Washington, DC: International Food Policy Research Institute.

Smale, M., P. Zambrano, G. P. Gruère, J. B. Falck-Zepeda, I. Matuschke, D. Horna, L. Nagarajan, I. Yerramareddy, H. Jones. 2009. *Measuring the economic impacts of transgenic crops in developing agriculture during the first decade: Approaches, findings, and future directions.* Food Policy Review 10. Washington, DC: International Food Policy Research Institute (IFPRI). http://www.ifpri.org/sites/default/files/publications/pv10.pdf http://dx.doi.org/10.2499/0896295117FPRev10

Takeshima, H. 2008. Ex-ante welfare effects from scale-neutral productivity growth for semi-subsistence orphan crops: Genetically modified cassava in Sub-Sahara Africa. Ph.D. dissertation, University of Illinois - Urbana-Champaign, United States.

——— . 2011a. "Distribution of Welfare Gains from GM cassava in Uganda Across Different Population Groups and Market Margins." *African Journal of Agricultural and Resource Economics* 6 (1): 1-20.

——— . 2011b. "Sensitivity of Welfare Effects Estimated by an Equilibrium Displacement Model: A Productivity Growth for Semi-Subsistence Crops in a Sub-Saharan African Market with High Market Margin." *Journal of International Agricultural Trade and* Development 7(1): 1–22.

Tomlinson, K. R., A. M. Bailey, T. Alicai, S. Seal, and G. D. Foster. 2017. "Cassava brown streak disease: historical timeline, current knowledge and future prospects." Molecular Plant Pathology 19: 1282-1294. doi:10.1111/mpp.12613

Tripathi, L., M. Mwangi, S. Abele, V. Aritua, W. K. Tushemereirwe, and R. Bandyopadhyay. 2009. "Xanthomonas Wilt: A Threat to Banana Production in East and Central Africa." *Plant Disease*, 93 (5): 440-451

Trigeorgis, L. and A. E. Tsekrekos. 2018. "Real Options in Operations Research: A Review." *European Journal of Operational Research*, 270 (1): 1-24.

Tushemereirwe, W. K., A. Kangire, F. Ssekiwoko, L. C. Offord, J. Crozier, E. Boa, E., M. A. Rutherford, and J. J. Smith. 2004. "First Report of Xanthomonas Campestris pv. Musacearum on Banana in Uganda." *Plant Pathology* 53 (6): 802.

Tushemereirwe, W. K., A. Kangire, J. Smith, F. Ssekiwoko, M. Nakyanzi, D. Kataama, C. Musiitwa, and R. Karyaija. 2003. "Outbreak of bacterial wilt on banana in Uganda." Infomusa (FRA) 12(2):6-8.

Tushemereirwe, W. K., O. Okaasai, J. Kubiriba, C. Nankinga, J. Muhangi, N. Odoi, F. Opio. 2006. "Status of Banana Bacterial Wilt in Uganda." *African Crop Science Journal* 14 (2): 73-83.

Uganda Bioscience Information Centre (UBIC). 2015. *Public knowledge and perceptions towards biotechnology and biosafety in Uganda.* National Crops Resources Research Institute, Namulonge, Uganda.

Uganda Bureau of Statistics (UBOS). 2010. *Uganda Census of Agriculture 2008/2009*. Kampala, Uganda. http://www.ubos.org/onlinefiles/uploads/ubos/pdfpercent20documents/UCAholding.pdf

——— . 2016. *National Population and Housing Census 2014, Main Report*. Kampala, Uganda.

——— . 2017a. *Statistical Abstract. Uganda.* Kampala, Uganda.

——— . 2017b. *Uganda National Household Survey 2016/17, September 2017*. Kampala, Uganda. www.ubos.org/onlinefiles/uploads/ubos/pdfpercent20documents/UNHS_VI_2017_Version_I_percent2027th_September2017.pdf

Uganda, Ministry of Finance, Planning and Economic Development. 2008. *National Biotechnology and Biosafety Policy*. Kampala, Uganda.

———. 2017a. *MAAIF Performance Review Report Fiscal Year 2016-2017.* Kampala Uganda. Extracted from https://www.agriculture.go.ug/wp-content/uploads/2019/09/MAAIF-Performance-Report-2016-2017.pdf

——— . 2017b. *Annual Economic Performance Report 2016/17*. Kampala, Uganda. December 2017.

———. 2019. *Performance of the Economy Report. – December 2019*. Kampala, Uganda. December 2019.

Uganda, National Council of Science and Technology. 2006. The Seeds Plant Act, 2006. Kampala Uganda. Extracted from: http://bch.cbd.int/database/attachment/?id=20093

———. 2007. *National Guidelines for the conduct of Containment research of Genetically modified organisms and Microbes in Uganda*. Kampala Uganda. Extracted from http://bch.cbd.int/database/attachment/?id=18207

———. 2011. *Revised National guidelines for Confined Field Trials.* Kampala Uganda Extracted from

US Agency for International Development - Famine Early Warning Systems Network (USAID FEWS NET). 2017. *Uganda – Staple Foods Market Fundamentals.* Washington DC. https://fews.net/sites/default/files/documents/reports/FEWS_NET_Uganda_Staple_Food_Market_Fundamentals_January_2017.pdf

World Bank. 2018. *Closing the Potential-Performance Divide in Ugandan Agriculture*. Washington, DC: World Bank.

Zambrano, A. P.; N. Paul, J. A. Chambers, J. B. Falck-Zepeda, and H. Hanson. 2019. *bEcon 4 Africa: An overview of the literature on the economic assessment of GE crops in the continent, 1996-2016*. IFPRI Discussion Paper 1841. Washington, DC: International Food Policy Research Institute.

Zhao, X., W. Griffiths, G. Griffiths, G and J. Mullen. 2000. "Probability Distributions for Economic Surplus Changes: The Case of Technical Change in the Australian Wool Industry." *Australian Journal of Agricultural and Resource Economics* 44 (1): 83–106.

ALL IFPRI DISCUSSION PAPERS

All discussion papers are available **here**

They can be downloaded free of charge

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
www.ifpri.org

IFPRI HEADQUARTERS
1201 Eye Street, NW
Washington, DC 20005 USA
Tel.: +1-202-862-5600
Fax: +1-202-862-5606
Email: ifpri@cgiar.org