Genetically modified crops in Kenya: the cost of delay

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Table of contents

Tables

Figures

Appendices

- Appendix 12. Explanation of the DREAM method for calculating the economic benefits of each genetically modified crop and the cost of delay.
- Appendix 13. Explanation of the Carbon Benefits Calculator method for estimating the environmental benefits of each genetically modified crop and the cost of delay.
- Appendix 14. Yearly values for output from analysis of economic benefits of Bt maize in Kenya using the DREAMpy model, medium scenario without delay.
- Appendix 15. Yearly values for output from analysis of economic benefits of Bt maize in Kenya using the DREAMpy model, medium scenario with delay.
- Appendix 16. Yearly values for output from analysis of economic benefits of Bt cotton in Kenya using the DREAMpy model, medium scenario without delay.
- Appendix 17. Yearly values for output from analysis of economic benefits of Bt cotton in Kenya using the DREAMpy model, medium scenario with delay.
- Appendix 18. Methodology for analysis of benefits of Bt maize in Kenya.
- Appendix 19. Methodology for analysis of benefits of Bt cotton in Kenya.
- Appendix 20. Methodology for analysis of benefits of 3R-gene potato in Kenya.

Forewords

Alliance for Science

In a world where around 258 million people across 58 countries and territories face acute food insecurity at crisis levels, it's hard to believe that a country would forego any innovation which could potentially increase the chance of safely providing more food for more people. Yet that is precisely the case with agricultural advancements such as genetic modification (GM) and gene editing, which has accelerated access to healthy nutritious food over the last 30 years since the introduction of the first GM foods in the US. On the African continent the spectres of hunger are all too real. In 2024, the African Development Bank (AFDB) highlighted widespread malnutrition and stunting with 216 million children suffering across the continent. Kenya ranked 90th out of the 125 countries in the 2023 Global Hunger Index and approved GM technology in 2020, but has failed to gain widespread approval for commercialization of staple crops. And yet Kenyan farmers battling severe climate change challenges are eager to get hold of improved varieties such as Bt maize, disease resistant potato, and Bt cotton that can now offer several advantages to improve yields and livelihoods for vulnerable communities who rely on agriculture for food and household income.

This report shows that delays in the approval of Bt cotton, Bt maize, and late blight disease-resistant potato have cost Kenya USD 157 million, and that they have the potential to create USD 467 million in benefits over 30 years. That's why the Alliance for Science is particularly happy to support advocacy work featuring not only the economic advantages of adoption of GM technology in Kenya but also better social outcomes at the household level. As incomes improve, children have greater chances to finish school, the pressures on family to meet basic needs eases, and out of these new opportunities emerge to transform individual lives and therefore better pathways out of poverty.

The Breakthrough Institute

To increase global food production while reducing deforestation, crop yields must grow. Greater adoption of existing technologies like high-quality seeds, genetically modified crop varieties, synthetic fertilizer, pesticides, and irrigation can all contribute to increasing crop yields. Unfortunately, opposition to genetically modified crops in Kenya—including a 10-year ban and subsequent court cases—has slowed the positive impact of this technology on crop yields. On the African continent, only 11 of 54 countries have commercialized a genetically modified crop.

This report shows that adoption of genetically modified crops in Kenya would not only generate large economic benefits, but would also—by increasing yields—lead to less deforestation, less habitat and biodiversity loss, and less global climate change. We estimate that adoption of Bt maize and Bt cotton in Kenya could reduce global greenhouse gas emissions by 0.23–0.72 million metric tons of CO_2 equivalents per year, equivalent to 0.2–0.7% of Kenya's total GHG emissions in 2020.

The cost of delay is high, and Kenyan policymakers should prioritize the timely commercialization of these and future genetically modified crops. In addition, the country should increase funding for agricultural research and development to adapt other improved crop varieties for Kenya, expand demonstrations of Bt cotton to increase farmer awareness, and grow capacity for regional seed production to expand options for farmers.

African Agricultural Technology Foundation (AATF)

ISAAA AfriCenter (International Service for the Acquisition of Agri-biotech Applications)
ISAAA AfriCenter has been dedicated to bringing the benefits of modern biotechnology to smallholder farmers across Africa. Our commitment has led to impressive progress, with the adoption of biotech crops expanding from three countries in 2018 to eight in 2023. AfriCenter actively promotes science-based biosafety and regulatory frameworks, advocating for policies that encourage the responsible use of biotechnology to enhance food security and improve livelihoods across the continent. Through initiatives like policy roundtables, national dialogues, media engagement, grassroots outreach, and our pioneering "seeing-is-believing" biotech study tours, AfriCenter has effectively engaged diverse stakeholders, fostering consistent and collaborative efforts to overcome policy challenges.

With the rapid advancement of information technology, concerns about the spread of false, unverified, and misleading information have intensified. Disinformation campaigns targeting new innovations, particularly in science and technology, have become increasingly aggressive. The World Economic Forum has identified misinformation as a global crisis. This surge of falsehoods around scientific innovations has not only delayed decision-making but also fostered public distrust, especially in areas like agriculture, health, and the environment. In Africa, mis/disinformation has significantly contributed to public hesitancy in accepting and adopting critical innovations that could address pressing challenges across the agriculture, health and environment sectors.

Modern biotechnology has often faced resistance, yet there is a growing demand for credible, accurate information on this and other bioscience innovations across the continent. This is evidenced by increasing inquiries from policymakers, academia, and the private sector.

Ensuring access to reliable, evidence-based information on agricultural biotechnology is crucial for informed decision-making.

This report, “Genetically Modified Crops in Kenya: The Cost of Delay,” examines the economic benefits Kenya stands to gain from the adoption of three biotech crops. It explores three adoption scenarios—low, medium, and high—and reveals how regulatory delays and slow decision-making processes have caused Kenya to forgo significant benefits. We hope this report will serve as a valuable resource for policymakers, the public, and private sector players, providing them with the insights needed to make informed, evidence-based decisions moving forward.

ISAAA AfriCenter remains committed to transforming agriculture and improving livelihoods by facilitating the adoption of modern biotechnology tools among smallholder farmers in Africa. By leveraging its extensive expertise and networks, AfriCenter aims to address the evolving challenges of African agriculture more effectively. We strive to inform Africa’s policies and markets on ethical and appropriate bio-innovations, contributing to the vision of a food-secure, healthy, and prosperous Africa.

International Potato Center (CIP)
As the third world food crop after wheat and rice, the potato is an important contributor to food security in the developing world. It provides nutritious food and cash income after a short growth cycle and does not compete with cereal cultivated areas. It is a carbohydrate rich crop with good quality protein, vitamin C, B12, potassium, and fibers.

The productivity increase needed to feed the nearly 8 billion people and the additional 2 billion in the next 30 years, cannot rely solely on conventional crop improvement. Potato crop improvement is particularly difficult and slow due to its genetic characteristics. For example, a resistance gene from a wild relative of the potato took 46 years to be introgressed by conventional breeding methods in a modern variety, whereas the same gene took only 3 years to be introduced using genetic engineering into elite potato varieties.

In Kenya, potato production reaches 1.9 million tons and is grown by 1.17 million potato farmers of which 98% are smallholder farmers. It is Kenya’s second most important food staple, after maize in gross production, and fourth in quantity consumed. Production constraints responsible for an average yield of 9 t/ha are well known and common to many less developed countries: low quality seed tubers, inadequate use of fertilizers, and pests and diseases.

Late blight disease (LB), caused by the oomycete *Phytophthora infestans*, the dominant disease of the potato worldwide, was estimated in Kenya to be responsible for 23% of potato production loss while 12% of the potato production costs are for controlling the disease. The cultivation of a biotech potato (produced by genetic engineering) which is completely resistant to LB disease was estimated to generate economic benefits of US$ 8.2 million annually with potential adoption rates ranging from 12% to 44% depending on the potato production area. The benefits in yield gain, measured as LB yield loss averted, and reduced production costs due to reduced fungicide uses will increase farms’ profits by 34%. The commercialization following good stewardship practices will ensure that this biotech potato will be accessible and affordable to all farmers in Kenya.

Executive summary

In order to feed a growing population, crop production must increase—ideally through increases in crop yields. However, though crop yields are increasing on a global scale, farmland area is also expanding through deforestation, which increases greenhouse gas emissions, destroys wildlife habitat, and reduces crucial ecosystem services. Since 2000, a global area over twice the size of Kenya has been cleared of native vegetation like forests to make space for more crop land.[1] The greenhouse gas emissions from deforestation then contribute to global climate change, which causes further negative impacts on food production. Agriculture has a huge impact as the sector is the biggest driver of deforestation globally. In contrast to farmland expansion, increasing crop yields can boost food production without causing additional deforestation.

Historically, yield improvement has been driven by the adoption of improved agricultural technologies such as crop varieties with enhanced genetic potential such as conventional hybrids complemented by fertilizers and use of Good Agronomic Practices (GAPs). Genetically modified (GM) crops have also shown tremendous potential to improve crop production in Kenya and across much of Africa. Despite this potential, the adoption of the technology has been delayed owing to legal challenges fueled by misinformation.

The history of GM crops in Kenya dates back over 20 years ago when research on Bt cotton started. Cotton became the first GM crop available to Kenyan farmers in 2020, making the country's cotton crop less vulnerable to the bollworm pest. Shortly after, three varieties of Bt maize became ready for commercialisation in 2021, which could protect farmers' crops from maize stem borer and fall armyworm damage but are still awaiting cabinet approval for commercialisation. Kenyan scientists are also developing disease-resistant GM varieties of cassava and potato.

Though Bt cotton has been commercialised, the approval and commercialisation processes for both Bt cotton and Bt maize have faced significant delays in Kenya due to a ten-year ban on the importation of GM crops (2012–2022) and subsequent court cases challenging the lifting of the ban. Though the ban was specifically on importation of GM crops, it was interpreted as a ban on commercialisation of GM crops within the country as well. These delays have had notable economic repercussions and have hindered progress in agricultural innovation.

This report assesses the potential economic and environmental benefits of three GM crops in Kenya—Bt cotton, Bt maize, and late blight disease-resistant potato—and the economic cost of the delays in the commercialization of these products. As a proxy for the cost of delayed adoption, we estimate the potential economic benefits of these three GM crops in terms of the additional crop yields and farmer profits, decreased pesticide use, and lower food prices for consumers attributable to the adoption of the technology using the DREAMpy model. We also estimated the environmental benefits in terms of reduced global greenhouse gas emissions due to reductions in deforestation using the Carbon Opportunity Cost approach.

Our simulation of benefits starts with the beginning of research and development of each GM crop variety and continues through commercial adoption—the exact years vary between crops due to their different development timelines. **We estimate that all together, five years of delay**

in approval of Bt cotton, Bt maize, and late blight disease-resistant potato may have cost Kenyan farmers and consumers 157 million USD (Figure 1).

Key findings by crop:

Bt maize

- We estimate that five years of unnecessary delays in Kenya's commercial adoption of Bt maize cost the country's farmers and consumers USD 67 million.
- Without five years of delay, Bt maize could have been available to farmers as early as 2019, generating significant economic benefits by reducing pesticide useage and thereby costs, increasing farmer yields and profits, and reducing food prices for consumers.
- We project that, by 2030, the total economic benefits of Bt maize without delay in release could have reached USD 218 million.
- If Kenya had started growing Bt maize in 2019, then in 2024—after the technology would have spread to more farmers—the country could have produced 194,000 tons more domestic maize. This is equal to 25% of imports received in 2022, and 14 times higher than the total maize food transfer from the UN World Food Programme to Kenya in 2023. The increase in domestic production could also strengthen the country's crop yields compared to Tanzania, its closest competitor in East Africa.

Bt cotton

- Due to five years of delay in the release of Bt cotton in Kenya, we estimate a cost to the country's farmers and consumers of USD 1.2 million.
- Without five years of delay, Bt cotton could have been released in Kenya in 2015 rather than 2020 and could have benefited Kenyan farmers and consumers by a total of USD 2.6 million by 2028.
- If Kenya had started growing Bt cotton in 2015, then in 2023—when the technology would have spread to more farmers—the country could have produced 650 tons more domestic cotton. This increase in domestic production could have replaced 12% of the cotton imported in 2022.
- Our projections are based on the current state of Kenya's cotton sector, with decreasing area and production. Bt cotton has the potential to help revitalise Kenya's textile industry, and earlier release of the variety may have helped prevent some of the ongoing decline in the sector.

Late blight disease-resistant potato:

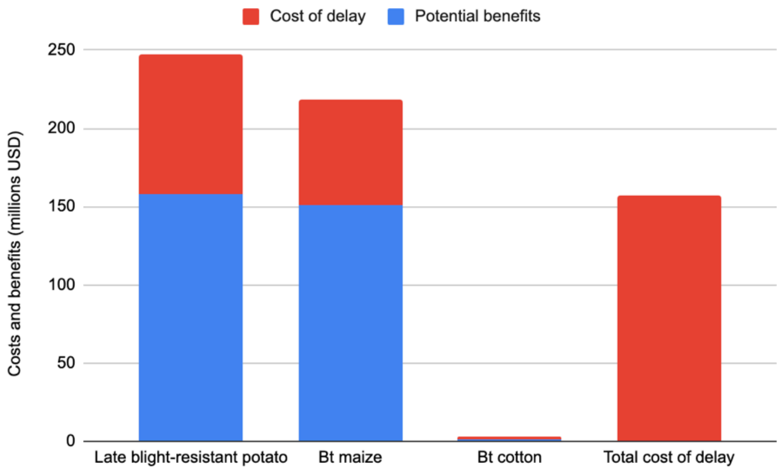
- We estimate that the release and commercialization of the late blight disease-resistant 3R-gene Shangi potato variety would benefit Kenyan farmers and consumers by USD 163 million and 84 million respectively, over a period of 30 years.
- A 5-year lag in the release of the 3R-gene Shangi would reduce the benefits to farmers and consumers by USD 59 million and USD 30 million respectively.
- An increase in domestic production of potato, a dietary staple for subsistence farmers, could strengthen the country's food security.

We project that if Bt maize and Bt cotton were widely adopted in Kenya, the increase in yields would reduce global deforestation and land use change due to agriculture, resulting in enough land-sparing to reduce global greenhouse gas emissions by 0.23–0.72 million metric tons of CO_2e per year, equivalent to 0.2–0.7% of Kenya's total GHG emissions in 2020.[2] We did not estimate the potential for GM late blight disease-resistant potato to reduce global greenhouse gas emissions because the crop is used almost solely as subsistence in Kenya, and therefore is not part of global agricultural trade that impacts global emissions.

Finally, adoption of GM crops can have many other advantages including a reduction in pesticide use, which benefits both human health and the environment; an increase in the country's food security and food/economic self-sufficiency resulting to decreased dependence on rising food aid and imports; and increased competitiveness within trading blocs like COMESA.

To capitalise on the full potential of GM technology, it is imperative that Kenya should avoid further costly delays and ensure the timely review and approval of future GM crops. This approach is essential not only for enhancing agricultural productivity but also for contributing to the reduction of agriculture's sizable global carbon footprint.

Figure 1. Five years of delay in approval of genetically modified late blight-resistant potato, Bt maize, and Bt cotton may have cost Kenyan farmers and consumers 157 million USD



Introduction

The status of GM crops in Kenya

The awareness and appreciation of genetically modified (GM) crops has grown among African farmers as evidenced by the number of countries planting biotech crops increasing from three in 2018 to eight in 2024. These eight countries—Ethiopia, Ghana, Kenya, Malawi, Nigeria, Sudan, Swaziland, and South Africa—have approved cultivation of at least one of four biotech crops: cotton, maize, soybean and cowpea. However, despite this progress, the adoption of GM crops in Africa remains slow and contentious. Investment in research and development in agricultural biotechnology has been unpredictable, with most countries lagging in the adoption of biotechnological products, and only a few crops advancing to commercialization. There is a need therefore to integrate biotechnology into Africa's agricultural development agenda to ensure food and nutrition security is improved across the continent. Kenya is among the African countries where GM crops have advanced the furthest, and where there is a functional regulatory environment to drive research and commercialization of genetically modified organisms (GMOs).

While Kenya technically and institutionally has a functional biotechnology regulatory regime, commercialization of GM crops has been delayed for many years. Following the infamous Seralini report in 2012,[3] the then-Cabinet instituted a 'GMO import ban' although this was never formally gazetted to become legally mandated, nor was it considered part of the official GM crop regulatory system. However, the 'import ban' had very negative impacts on the commercial adoption and cultivation of GM food crops in Kenya. After the ban was lifted by the incoming Ruto government in 2022, anti-GMO groups responded with a flurry of legal cases aiming to stop the adoption of GM crops in Kenya. The legal cases have been standing in the way of commercialising new GM crops in Kenya since the ban was lifted in 2022.

These court cases were accompanied by a barrage of misinformation about GMOs—including that consuming GMOs would make men grow breasts, make children be born with 15 fingers, and that the Bt gene is integrated into soils and makes them toxic—that was even disseminated by senior politicians. The Alliance for Science performed a study of media coverage of GMOs in Kenya in 2023 that found 40% of media coverage of the subject contained unchallenged misinformation.[4]

In late 2023, the Nyahururu environment court dismissed a case challenging the release and planting of Bt maize. The remaining four cases were consolidated and sent to the High Court Human Rights Division. A ruling on the consolidated petition was initially due in July 2024, then was delayed until October 31, 2024, and delayed again until November 7, 2024. On November 7, 2024, the consolidated petition was finally dismissed.

With recently concluded court cases and major national policy decisions, the status of GMO crops in Kenya continues to be intensely debated in the media and elsewhere. While opponents make great play of the potential risks of GMOs, often utilising misinformation to bolster their case, the benefits of adoption are less clear to farmers, policymakers and consumers because there is insufficient high-quality research that quantifies it.

This report remedies the information deficit and quantifies the benefits of three GM crops in Kenya. However, because adoption of these crops has either been delayed or is still blocked, this report analyses the costs of delay, sometimes also called the "opportunity cost" or "foregone benefits". Though there is an extensive history of analyses of the potential benefits of GM crops worldwide, there are few studies focused on Kenya specifically. In Kenya Bt cotton has been commercialised, and Bt maize, late blight disease-resistant (LBR) potato, and disease-resistant cassava are in the pipeline towards commercialization. This report focuses on Bt maize, Bt cotton, and LBR potato and the cost of delaying their commercialization as well as their potential benefits, including economic benefits to Kenyan farmers and consumers, environmental benefits of reduced greenhouse gas emissions, and improvements in Kenya's agricultural self-sufficiency.

Though quantifying and challenging misinformation is important and necessary, it can only be part of the story. The other important element in enabling policymakers to have a more evidence-based approach and to improve public understanding is to conduct research which informs people on the potential benefits of GMOs. This shifts the debate in a more science-based direction by putting data on the table that sheds light specifically on key issues of concern such as farmers' incomes, food security and pesticide use.

To generate this vital data, a multi-organisation project team was assembled comprising the African Agricultural Technology Foundation (AATF) through the Open Forum on Agricultural Biotechnology (OFAB) project, the Breakthrough Institute, the Alliance for Science, and the International Service for the Acquisition of Agri-biotech Applications (ISAAA). Researchers at the International Potato Center (CIP) contributed their work on the benefits of GM potato in Kenya. Experts on key crops and other areas were consulted during this process, as were other organisations that have engaged in studies of this kind.

The process of regulating GM crops in Kenya

In Kenya's current system for GM crop regulation, developers may first apply to the National Biosafety Authority (NBA) for approval for contained use to conduct research on the GM crop in the laboratory and greenhouse. However, this step is not always necessary as Kenyan biosafety regulations have a provision for data transportability that allows researchers to use data generated from lab findings and CFT in other countries, where the only steps left are to use breeding to create locally adapted varieties. Second, developers apply to NBA for approval for limited environmental release to conduct Confined Field Trials (CFTs). Third, they conduct an Environmental Impact Assessment (EIA) and apply to the National Environment Management Authority (NEMA) for approval of the EIA to begin National Performance Trials (NPTs). Finally, after NPTs conclude, NBA approves the GM crop for unlimited release or commercialization, and Kenya Plant Health Inspectorate Service (KEPHIS) approves varieties from NPTs for commercial release.

NBA's timeline for conducting GM crop reviews is 90–150 days, as stated in Kenya's biosafety regulations; however, historically the agency has often substantially overrun the 90–150-day timeline. One reason is that the agency must often pause review after requesting additional information from the crop developer, and only resume once the agency receives it. Another reason reviews can take over 150 days is that during the ban, the Cabinet had to give the final approval before commercialization. A reliable timeline for review is important so that developers of GM crops can plan sufficient funding and resources to continue the project to the end, particularly when using grant funding.

Historical perspectives on GM maize in Kenya

Maize forms a large part of Kenyan diets in the form of ugali and *Githeri*, and a majority of households get most of their calories from maize; a small proportion of the country's total maize production is used for animal feed. In Kenya, smallholders produce 70% of all maize on 80% of the cultivated area grown with maize.[5] Maize stem borer and Fall armyworm pests cause widespread damage to crops in Kenya almost every year, with yield loss averaging 15–20%. Though good control of stem borers is possible with insecticides, smallholders generally lack access to both this knowledge and to appropriate insecticides. Bt crops reduce crop damage from pests, especially in the absence of insecticide application.

Development of Bt maize in Kenya began with the Insect Resistant Maize for Africa (IRMA) project in late 1999, and varieties were ready for commercial release after NPTs ended in 2021. These GM maize varieties contain a transgene that was transferred from a naturally occurring soil bacteria called *Bacillus thuringiensis*, and they produce a toxin that kills the larvae of some pests including stem borers. For over a decade, the US, Brazil, Argentina, South Africa, and Canada have been growing over a million hectares each of biotech maize (including Bt), and this year Nigeria became the second African country to begin commercial planting of Bt maize, popularly known as the TELA Maize .[6,7]

The TELA Maize Project is a public-private partnership led by the African Agricultural Technology Foundation (AATF) working towards the commercialization of transgenic drought-tolerant and insect-protected (TELA) maize varieties to enhance food security in sub-Saharan Africa. Launched in 2018, the TELA Maize Project builds on progress made from a decade of breeding work under the Water Efficient Maize for Africa (WEMA) Project. TELA maize varieties contain both conventionally bred drought tolerance and Bt genes for insect protection.

DroughtTEGO® hybrids contain the same conventionally bred drought tolerance as the TELA hybrids and are already grown in Kenya. Recent external impact assessment on DroughtTEGO® hybrids in the East African countries of Kenya, Tanzania, and Uganda showed a high adoption rate of 39% in Kenya, 17% in Uganda, and 11% in Tanzania. The study also reported that Kenya had the highest maize productivity of 3.6 t/ha relative to the non-adopters of DroughtTEGO® hybrids with a productivity of 2.2 t/ha (64% yield increment among adopters over non-adopters). Farmer income was also highest in Kenya with US$ 3,532/ha among adopters relative to non-adopters with income of US$2,045/ha (73% increment). The benefits of DroughtTEGO® could be greatly increased by adoption of the TELA hybrids that contain the Bt gene for insect protection. However, the three TELA Bt hybrids (WE1259B, WE3205B and WE5206B) recommended for release in 2021 were delayed until at least 2024 by the court case.

Historical perspectives on GM cotton in Kenya

Historically, cotton production in Kenya was strongest in the 1980s and 1990s, with total production peaking in 1984/1985.[8] Since then, cotton production has been declining in Kenya, along with neighboring countries Ethiopia and Uganda.[8] Cotton seed quality in Kenya is generally poor, being untreated and mixed, and dominated by varieties introduced 2–3 decades ago.[8] To address these issues, the Kenya government included cotton as a priority crop in its blueprint strategy, Vision 2030. Kenya's Vision 2030 identifies cotton as a key sub-sector with the potential to benefit the 8 million people in the drier areas that cover 87% of the country.[9,10] Since in Kenya cotton is produced on only 10% of the potential land that is suitable for it,[8] the sector could benefit from expanding the cultivated area in addition to increasing yields. Compared to the rest of East Africa, Kenya's total cotton production as well as cotton yields are much lower than Ethiopia, Uganda, or Tanzania (author's calculations using data from FAOSTAT).

The government set up the Cotton Development Authority (CODA) to coordinate the revitalization of the cotton industry in 2006.[10] The country also has a strong regional position under the African Growth and Opportunity Act (AGOA), with an increase in apparel exports to the US from 16% in 2004 to 37% in 2014.[11] Kenya has strong garment manufacturing capacity,[12] but the country doesn't produce enough cotton lint for its textile; imports from Tanzania and Uganda fill the shortage.[13] Currently, Kenya produces 1,254 metric tonnes of cotton lint, but there is a deficit of 7,586 metric tonnes between this production and the consumption of 8,840 metric tonnes.[14] The deficit is filled using imports that cost Kenya KES 1.7 billion annually.[14]

Kenya's cotton industry faces many challenges to increasing production, including pests that damage crops. The larva of the cotton bollworm is the main cotton pest throughout Africa, causing damage in up to 90% of bolls when untreated,[15] leading to lost cotton production. One way to manage cotton bollworm pests is the use of insecticides, which are widely applied to the crop—of the total insecticides used on crops in Africa, 25% are sprayed onto cotton.[8] Unfortunately, these pesticides pose significant health hazards for many farmers and labourers and cause extensive environmental pollution. Another way of decreasing the damage from cotton bollworm is ensuring seed quality. Farmers' access to quality seeds is the first and most important starting point toward meeting Africa's continental and individual country agricultural goals such as food security, nutritional security, improved household incomes, improved livelihoods among others. In 2008, the Government of Kenya recognized the importance of quality and high yielding cotton varieties, and called for improving availability to farmers.[16] The government also enacted laws, regulations and policies to strengthen the cotton value-chain and instituted institutional reforms such as establishment of Kenya National Biosafety Authority, the Fiber Directorate, the Cotton Development Authority and revitalization of Rivatex Textile Industry.

In 2020, Kenya approved commercial release of improved insect resistant and hybrid cotton seeds. In 2016, a total of 8 African countries either planted, actively evaluated field trials or moved towards grant approvals for the general release of Bt cotton (Cameroon, Ethiopia, Kenya, Malawi, Nigeria, South Africa, Sudan, Swaziland). South Africa was the first country on the African continent to adopt Bt cotton for commercial production in 1998. Burkina Faso was the second country to adopt Bt cotton in 2008, followed by Sudan in 2012 and Malawi and Kenya in 2020.

In some African countries, Bt cotton has made progress only to be blocked again. In Cameroon, field trials on GM cotton were carried out in the Northern Region of Cameroon from 2012 to 2020. However, in 2020, the trials were terminated due to a change in national priorities. In Burkina Faso, the government temporarily suspended the growing of Bt cotton in 2016 to address a concern about fibre length observed in the varieties farmers had grown over the last eight years. Trials have started again in Burkina Faso which may see the return of Bt Cotton in 2026.

While Bt cotton was commercialised in Kenya in 2020, the technology still has a long way to go in the country. Not only does Kenya need a more reliable and lower cost source of Bt cotton seeds for farmers, but high input costs are also a problem. The country must also better support the cotton industry overall, including by modernizing ginning facilities to increase ginning efficiency. The Bt technology can contribute to revitalising Kenya's cotton sector but must be paired with other improvements like better farmer access to high-quality seeds and education and extension interventions to improve pesticide application.

Historical perspectives on GM potato in Kenya

Potato late blight is one of the most important diseases affecting potato production in Kenya, particularly in the cool highlands, where potatoes are mainly grown.[17–20] High incidences of potato late blight are due to inappropriate use of chemicals to control the disease, lack of varietal resistance, and a poor seed system among other factors.[17] Although late blight-resistant potato varieties have been developed over time using conventional breeding methods,[21] lasting resistance has been elusive,[18] where the varieties have either lost their resistance or degenerate with time.[17]

Through the Feed the Future Global Biotech Potato Partnership (GBPP), the International Potato Center (CIP), as part of a consortium managed by Michigan State University (MSU), contributes to the development of genetically engineered 3R-gene late blight-resistant varieties. The technology consists of the simultaneous introduction of three R (resistance) genes from wild relatives into farmers and consumers 'preferred' potato varieties. To provide durable resistance, the resistance genes used are chosen to provide broad-spectrum resistance, making it difficult for disease strains to overcome them. In addition, the resistance genes are introduced simultaneously, requiring a disease strain to adapt and overcome the multi-layered defense simultaneously, which is additionally unlikely. In Kenya, three varieties were recommended for transformation. These were the 3R-gene Asante, 3R-gene Shangi, and 3R-gene Tigoni.

Literature review: previous economic analyses of GM maize, cotton and potato crops in Kenya

This section presents an overview of studies that have assessed the economic impact of GM crops in Kenya. Generally, there are multiple studies that have focused on maize, while GM cotton and potatoes have received limited attention in literature.

Several studies have previously estimated the potential economic impacts of investments in GM and other improved maize varieties in Kenya (Table 1).[5,22–24] All these studies converge on the finding that improved maize technologies, including GM maize, have substantial positive economic benefits.

De Groote *et al.* (2011) estimated the potential benefits of Bt maize in Kenya at 208 million USD over 25 years, with only about 7 million USD spent on research to develop the technology.[22] Subsequent studies on Bt maize in Kenya use data from De Groote *et al.* (2011) on yield loss due to stem borers and potential yield increase due to the Bt trait, as well as reduction in input use.[5,23] Nagarajan, Naseem, and Pray (2016) estimated the economic benefits of GM Bt, herbicide tolerant, and drought tolerant maize traits in Kenya.[5] They calculated the total potential economic benefits due to adoption of the Bt trait alone, from 2016–2025, to be 108 million USD, with 45 million USD accruing to farmers and 63 million USD to consumers.[5] Wesseler *et al.* (2017) estimated the foregone benefits of adoption of GM Bt maize in Kenya.[23] They report, based on an estimate from organisations involved in its development—Kenya Agricultural Research Institute (KARI; name changed in 2014 to KALRO, Kenya Agricultural and Livestock Research Organization) and CIMMYT—that Bt maize could have been commercialised in Kenya by 2006, considering that the IRMA project started in 1999 and the first national performance trials of Bt maize were in 2004.[23] They found that the total potential economic benefits due to commercialization is about 475 million USD, the benefits from reduced malnutrition are about 795 million USD, and that Kenya could have saved 440–4,000 lives by adopting GM Bt maize in 2006.[23] The total cost of a 10-year delay in approval of Bt maize in Kenya was an estimated 419 million USD.[23]

Willy *et al.* (2021) estimated the benefits of conventionally-bred drought tolerant maize in Kenya, known as DroughtTEGO®.[24] The varieties of Bt TELA maize that are ready for commercialization in Kenya contain both the MON810 Bt trait and the drought tolerance attribute of DroughtTEGO® To create the TELA maize varieties, the MON810 Bt gene was introgressed into the drought-tolerant DroughtTEGO® variety to create a product that has double protection from both pests and drought. Therefore, the benefits we estimate of the MON810 Bt trait in Kenya are in addition to the benefits of the drought-tolerance trait estimated by Willy *et al.* (2021).[24] They estimate that the total expected economic benefits from 2017–2036 is 2,120 million USD, which is about 16 times the amount spent on research and extension to develop the technology.[24]

The differences between the estimates in these studies are due to many factors, including different base years and time periods, and assumptions about maize crop loss due to stem borers, the yield advantage of the Bt trait, and supply and demand elasticities, among others. All used an economic surplus model.

Table 1. Previous studies in Kenya estimate the benefits of Bt maize from USD 108–208 million, and drought-tolerant maize at USD 2120 million

Reference	Economic benefits (USD millions)	Years	Crop and trait
De Groote *et al.* (2011)[22]	208	25	Bt maize
Nagarajan, Naseem, and Pray (2016)[5]	108	10	Bt, herbicide tolerant, and drought tolerant maize
Wesseler *et al.* (2017)[23]	157	10-year delay	Bt maize
Willy *et al.* (2021)[24]	2120	20	DroughtTEGO® maize

Wesseler et al. (2017) results cited are the cost of a 10-year delay in commercialization of Bt maize.[23] Results from the other three studies are benefits of commercialization. All benefits are total economic surplus.

We offer an updated estimate of the cost of delays throughout the development of Bt maize in Kenya. In addition to estimating economic benefits as in the studies above, we also estimate the potential reduction in global greenhouse gas emissions, food imports and food aid, and impact on Kenya's strength of maize production within East Africa.

In the case of cotton, few studies have previously estimated the potential economic impacts of investments in GM Bt cotton in Kenya. One study estimates the potential economic benefits of Bt cotton in multiple countries including Kenya over a 25-year period.[25] Across four different adoption scenarios, the total economic benefits to Kenya range from 0.28–2.22 million USD, with 0.13–0.86 accruing to consumers and 0.17–1.18 to producers.[25] The average of these economic benefits is 6–48 USD per hectare using a total area under cotton of 46,000 hectares with an average yield of 0.65 MT/ha, and total production of 30,000Mt.[25] Studies in other countries generally showed increases in farmer income. For example, in Burkina Faso, farmers that grew Bt cotton had an average profit of over twice that of farmers that grew conventional cotton—USD 150/ha vs USD 70/ha, respectively.[15] And in India, growing Bt cotton increased farmer profits by 50%.[26]

Unlike maize and cotton, we find a dearth of literature on the potential economic benefits of GM potatoes focused on Kenya. The few existing studies on the potential economic benefits of biotech potatoes in Kenya have mainly focused on sweet potatoes.[27] Studies on biotech 'Irish' potatoes have mainly focused on their development,[28] and ability to provide extreme resistance to late blight diseases.[29–31]

We offer an estimate of the potential benefits of GM late blight-resistant potato in Kenya. The results presented here are from research by CIP, in collaboration with local partners, and are also in press at the journal PLOS ONE.

Methodology

Data types and sources

To achieve the objectives of this study, secondary data were obtained from scientific publications, websites including FAOSTAT, the World Bank, IndexMundi, and AfricaFertilizer; and databases at AATF and Tegemeo Institute of Agricultural Policy and Development-Egerton University. Data requirements for the economic analysis included crop yields, prices, area under production, production quantity, and consumption quantity (all input data are listed in Appendix 1 and Appendix 3 and discussed in the methodology sections for each crop). Other key parameters needed for the analysis included quantities and prices, impact of technology on producers' cost, adoption rate, supply and demand elasticities, and research costs, which are described in the sections for each crop and in Appendix 1, as are the discount rates used. For the analysis of climate benefits, this data included the same values for crop yields and area under production as the economic analysis.

For the analysis of the 3R-gene potato varieties, data was also collected from potato experts and local and global online statistical databases, and a validation workshop was held to validate the estimates obtained by experts. Except where otherwise noted, we used national data on crop production (and anything else like prices) from FAOSTAT up until 2019. Data quality for 2020–2023 is poor due to the COVID-19 pandemic and changes in administration, so we used the average of 2017–2019 data for 2020–2023 and assume no shocks in those years. With more accurate data on crop production for 2020–2023, we could incorporate the impact of shocks during that period including the COVID-19 pandemic and Russia's war on Ukraine.

Analysis of economic benefits

This report assessed the costs of Kenya's delayed approval of three GM crops by estimating the economic benefits of the crops with and without delay, as well as the potential climate mitigation benefits. For each crop, we modelled three main scenarios—low benefits, medium benefits, and high benefits—both with and without delay. The three scenarios were differentiated by the magnitude of yield increase due to the GM crop trait, the percentage of cultivated area grown with the GM crop variety compared to non-GM varieties (also called percent adoption), and the change in the cost of inputs like pesticides and seeds for farmers that grow the GM variety.

Everything that happens from the beginning of the R&D process for a new technology, through to commercialization and adoption, is important when considering whether the investment in R&D is worthwhile. If factors like the court cases cause undue delays in the path of the GM crop to commercialization, then the potential benefit is reduced. To see what Kenya has lost from a 5-year delay in commercialization of GM crops, we calculated the economic impact of the new GM crop for both farmers and consumers, comparing scenarios with and without delays.

To estimate the potential economic benefits of Bt maize and cotton and late blight-resistant potato in Kenya, we used an economic surplus partial equilibrium model that runs using the DREAMpy software developed by IFPRI (detailed in Appendix 12).[32] We chose this approach because it requires limited input data, which is scarce for agriculture in Kenya, and is well-represented in the literature on benefits of GM crops.[22,25,33,34] The economic surplus model estimates the shift in the supply curve due to the introduction of GM crop technology, which can reduce the cost of production for farmers and thereby reduce prices for consumers. The resulting changes in production and consumption are termed the producer surplus and the consumer surplus and represent the changes in consumer and producer welfare as a result of the introduction of the new technology. The details of the economic surplus model (ESM) run by DREAMpy are described in the initial manual,[35] and we summarize the DREAMpy approach in Appendix 12. Key parameters needed to model each scenario with DREAM (quantities and prices, impact of technology on producers' cost, adoption rate, supply and demand elasticities, and research costs) are described in the sections for each crop and in Appendix 1, as are the discount rates used. Considering that some of these benefits to producers and consumers accrue in the future, we use discounting to normalise these benefits as well as costs to a single year, which is to estimate their Net Present Values.

The DREAMpy economic surplus model includes several important assumptions: that there are no transaction costs, that the markets function well, that prices and quantities of commodities other than the one focus of the model are fixed, that changes in prices but not changes in income affect economic surplus, that input markets don't change, and that farmers will maximise profits or minimise costs.[33] The model is also very sensitive to some of the inputs, including elasticities of supply and demand, changes in yield due to the new technology, and costs of inputs like fertiliser. We perform a sensitivity analysis to assess the impacts of these variables on the total economic surplus, as detailed in the crop-specific sections below.

To model the economic benefits of each crop in Kenya, we ran a simulation from the year when research and development began in the country through subsequent years after commercialization when benefits are expected to accrue. For each of the main scenarios—low, medium, and high—we used either the year when the crop is expected to be commercialised (or in the case of cotton when it was commercialised), or the year when the crop could theoretically have been commercialised without delays. For Bt maize, research in Kenya began in 2000 and delays have prevented commercial cultivation until the present day, though the varieties could have been commercialised in 2019 without delays. For Bt cotton, research in Kenya began in 2001 followed by commercialization in 2020, and the varieties could have been ready for commercialisation in at least 2015 without delays. For late blight disease-resistant potato, the simulation base year is 2020, with commercialization in 2028. In the scenarios with delays, we extended the total simulation by the number of years of delay to model the same adoption period. We also included the cost of research and development, as well as regulatory compliance, in our estimation of economic benefits.

When estimating economic benefits, scenario analysis becomes critical. Estimating the benefits under different scenarios helps to understand all the possible outcomes considering the possible situations in real life. In the next section we describe the scenarios that were considered in the study.

Description of scenarios considered in the study

We defined three scenarios for low, medium and high benefits for each crop. The scenarios have different values for yield benefit, change in cost of production, and maximum adoption. The medium scenario is the one we view as most likely to occur. Later, in the sections for each crop we detail the methods used to develop the values for the scenarios.

Table 2. Values defining the low, medium, and high scenarios for analysis of economic and environmental benefits of Bt maize in Kenya

Scenario	Yield increase	Maximum adoption	Change in cost of inputs
low	7.5%	40%	6.1%
medium	10.3%	60%	-1.0%
high	15.7%	72%	-4.5%

Table 3. Values defining the low, medium, and high scenarios for analysis of economic and environmental benefits of Bt cotton in Kenya

Scenario	Yield increase	Maximum adoption	Change in cost of inputs
low	15%	20%	0.4%
medium	20%	70%	-4.6%
high	40%	90%	-10.2%

Table 4. Values defining the scenarios for analysis of economic benefits of 3R-gene Shangi potato variety in Kenya.

1. Yield Change with LBR variety adoption in baseline scenario (%)			
Fungicide application in a cropping season	**North Rift**	**South Rift**	**Central and Eastern**
Untreated	91.7	55.0	61.3
Tri-weekly	22.1	17.5	15
Bi-weekly	9.2	35	10
Weekly	0	0	
2. Maximum adoption rate (%)			
Scenario	**North Rift**	**South Rift**	**Central and Eastern**
Minimum	8	30	10
Most likely	12	44	20
Maximum	17	53	30
3. Cost Change with LBR variety adoption (%)			
Spraying frequency	**North Rift**	**South Rift**	**Central and Eastern**
Untreated	0	0	0
Tri-weekly	-14	-13	-7
Bi-weekly	-17	-18	-9
Weekly	-25	-30	

Untreated means that no fungicide is applied to treat potato late blight, meaning other pesticides may be applied. Tri-weekly fungicide application totals approximately 3 sprays per season, *bi-weekly totals 4, and weekly totals 7. Cost change with LBR variety adoption assumes that no spraying takes place with LBR variety adoption.*

Analysis of environmental benefits

In order to estimate the potential reductions in global greenhouse gas emissions associated with crop yield increases in Kenya, we used the Carbon Benefits Calculator,[36] which is based on the ability for land to store carbon if it is not used for agriculture. We describe the Carbon Benefits Calculator approach in more detail in Appendix 13. This method assumes that an increase in crop yields in one location leads to a decrease in farmland expansion in the rest of the world, and therefore a decrease in greenhouse gas emissions from deforestation and clearing of other vegetation.[36] There is strong evidence that increasing crop yields in one location reduces deforestation and other land-use change globally.[37] These reductions do not always occur within the country or region where yields rise, and factors like whether a country is highly integrated in global markets can affect how much increases in productivity decrease deforestation globally vs locally.

For our analysis, inputs to the Carbon Benefits Calculator model consisted of the yield increases and adoption rates for each GM crop from the low, medium, and high scenarios. We assume no change in fertiliser use between the Bt and no-Bt scenarios. In our analysis, we present the total GHG emissions reduction assuming that all increases in crop yields in Kenya lead to a decrease in crop production elsewhere in the world, rather than any leading to increases in crop production (often known as rebound). We use the default values for all parameters in the Carbon Benefits Calculator model, including default production emissions and a discount rate of 4%.

Results

The economic and environmental benefits of Bt maize in Kenya

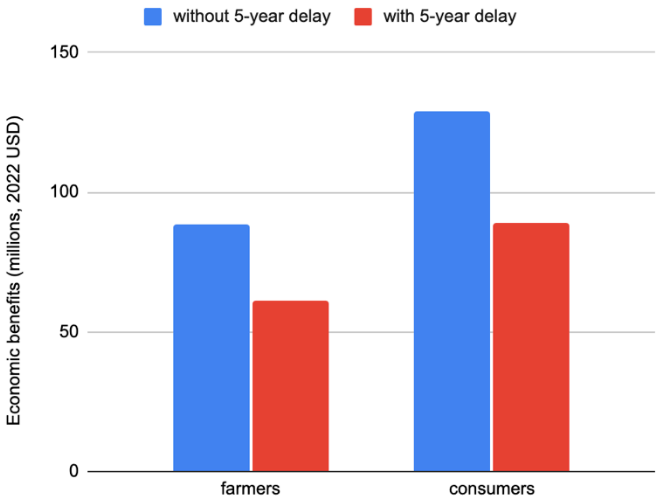
This section presents the results of our analysis of the potential economic and climate benefits of Bt maize in Kenya, and the cost of delaying adoption. Our analysis uses a baseline of the current state of Kenya's maize industry, including growth rates of maize production and demand, and we estimate potential yield increases and adoption rates of the Bt trait.

Economic benefits of Bt maize in Kenya

Table 5 and Figure 2 presents the DREAMpy economic surplus model, with detailed results presented in Appendix 2. These results indicate that if Kenya had begun growing Bt maize in 2019—when the technology could have been ready for commercialization without delays—Kenyan farmers and consumers could have gained an estimated USD 218 million in benefits by 2029 (medium scenario, Table 5; Appendix 2). Since there have been at least 5 years of delay and Bt maize still has not been released to Kenyan farmers as of October 2024, farmers and consumers may only gain USD 151 million by 2034 (medium scenario, Table 5; Appendix

2). Therefore, 5 years of delay may have cost Kenyan farmers and consumers USD 67 million (Figure 2; Appendix 2).

Figure 2. Five years of delay in approval of genetically modified Bt maize may have cost Kenyan farmers and consumers USD 67 million



Results presented are from the medium, most likely scenario. The cost of delay is the difference between the value of economic benefits without (blue) and with (red) regulatory delay in millions 2022 USD.

Though the estimated degree of economic benefits to Kenyan farmers and consumers varies widely between the low, medium, and high scenarios, even in the low scenario with the smallest yield increase, cost decrease, and area grown with Bt maize (Table 3), adoption of Bt maize would generate over USD 12 million in benefits for both farmers and consumers (Table 5). And though benefits to consumers are higher than benefits to farmers, adoption of Bt maize in the medium scenario would generate at least USD 61 million for each group (Table 5).

Table 5. Kenyan farmers and consumers could gain USD 33–445 million in economic benefits from Bt maize

Scenario	Delay?	Benefits to farmers	Benefits to consumers	Total benefits	Costs	Benefits-Costs	Benefits/Costs	Internal Rate of Return
		(millions 2022 USD)						(%)
high	no	182	263	445	8.4	436	53	34
high	yes	126	182	308	8.4	299	37	27
medium	no	89	129	218	8.4	209	26	29
medium	yes	61	89	151	8.4	142	18	24
low	no	19	28	47	8.4	39	6	20
low	yes	13	19	33	8.4	24	4	17

*Benefits presented here are the present value of the change in producer and consumer surplus due to adoption of technology, in millions 2022 USD. The present value of R&D costs is 8.4 million in 2022 USD in these scenarios, or 2.16 million in 2001 USD (*Appendix 2*).*

For all scenarios—low, medium, and high—the internal rate of return is between 17% and 34%, all of which are above the discount rate of 10%, and the benefit-cost ratios are all over 1, suggesting that the investment is worthwhile (Table 5; Appendix 2). The costs of developing Bt maize in Kenya have been mainly paid by international organisations, whereas the economic benefits are mainly gained by Kenyan farmers and consumers. Though the Kenyan government was not a main funder of Bt maize development, the benefit-cost ratio presented can still provide guidance as to the costs and benefits of funding a similar project in the future.

The above estimates of economic benefits do not include the potential benefits of reduced food imports. If Kenya had started growing Bt maize in 2019, then in 2024—after the technology would have spread to more farmers—the country could have produced 194,000 tons more domestic maize (Appendix 14). With this increase in domestic production, Kenya could replace 25% of imports received in 2022 (most recent year with data available on FAOSTAT). This amount is 14 times higher than the total maize food transfer from the UN World Food Programme to Kenya in 2023.[38] Therefore, by increasing domestic maize production, Kenya could enhance food security while strengthening food self-sufficiency. In East Africa in 2019, Kenya ranked fourth behind Ethiopia, Uganda, and Tanzania for maize yields, and third behind Ethiopia and Tanzania for total maize production. If Kenya's maize yields were 10% higher for 60% of the country's production due to the Bt trait, it could have achieved higher yields than Tanzania in two of the three years from 2017–2019 due to adoption of Bt maize.

We report the estimated benefits to Kenya of growing Bt maize with the MON810 trait, which is present in the current varieties of TELA maize awaiting commercialization. TELA maize also has a drought-tolerant genome like that of DroughtTEGO®, which is conventionally bred non-GM and has been grown in Kenya since 2017. Another study estimated the benefits of DroughtTEGO® maize in Kenya at USD 2.1 billion over 20 years,[24] and we would expect similar benefits to result from the drought-tolerant genome of TELA maize in addition to the benefits of the Bt trait.

The benefits of Bt maize may vary widely within Kenya; we predict the Bt trait will mainly increase yields in the lowland, mid-altitude, and transitional zones rather than the highlands, because they mainly protect against the stem borer species *Chilo partellus*, which does the most damage in those regions. While the regions where yields increase may experience economic benefits due to higher production even if prices decrease, regions where Bt maize does not increase yields could experience lower profits due to a decrease in prices within the country. Therefore, our results suggest benefits to the country as a whole but provide limited information about how those benefits may be spread out within different regions of Kenya.

We assume little to no benefit from the MON810 Bt trait in TELA maize in the highlands, considering that it provides low protection against *Busseola fusca* which is the main source of maize crop loss to stem borers in the highlands. However, MON810 provides some small protection against *B. fusca*,[39] so farmers in the highlands may still see some degree of protection. In addition, maize farmers in the highlands and all regions may also benefit to some degree from partial protection of the MON810 Bt trait against fall armyworm, which we also did not estimate in this report.

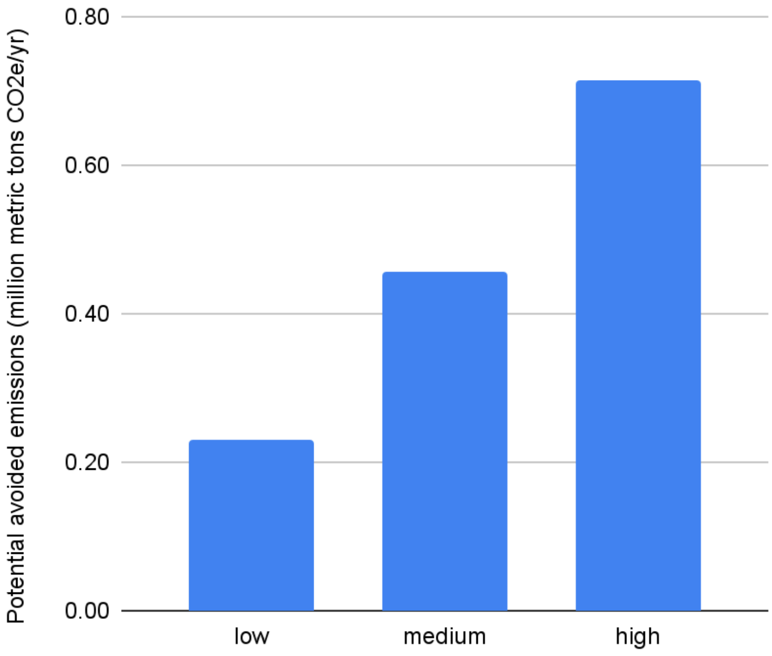
Sensitivity analysis of the economic benefits of Bt Maize

To test the robustness of our results from the low, medium, and high scenarios, we vary additional inputs to the DREAMpy model including supply elasticity, supply and demand growth rates, adoption lag, and discount rate (values for sensitivity analysis are listed in Appendix 1). Most of the sensitivity analyses involve varying inputs in the medium scenario that do not otherwise change between the low, medium, and high scenarios. Results of all sensitivity analyses are listed in Appendix 2. In all the sensitivity analyses the total economic benefits increase or decrease, but our results still suggest that the investment in Bt maize in Kenya is worthwhile given that the internal rate of return (IRR) remains above the discount rate, and the benefit-cost ratio remains over 1 (Appendix 2). This includes decreasing the adoption rate in the low scenario from 40% to 20%. Changing the discount rate essentially decreases the impact that time has on the value of money, meaning that the cost of a 5-year delay also decreases (Appendix 2).

Environmental benefits of Bt maize in Kenya

The results presented in Figure 3 indicate that if Kenya grew Bt maize in 2019, global greenhouse gas emissions could have decreased by 0.23–0.71 million metric tons of CO_2 equivalents per year—equal to 0.2–0.7% of Kenya's total GHG emissions in 2020.[2] The different estimates for the low, medium, and high scenarios are due to both the degree of yield increase from the Bt trait in maize and the percent of total maize cultivation made up of Bt varieties.

Figure 3. Growing Bt maize in Kenya could decrease global GHG emissions by 0.23–0.71 million tons CO_2e/year



Land use change emissions are calculated using the carbon opportunity cost approach. All calculations conducted using the Carbon Benefits Calculator v1.0.[36]

The reduction in emissions across all scenarios are due to avoided emissions from deforestation (Figure 3). By increasing yields, adoption of GM maize reduces the emissions intensity of maize production in Kenya. Kenya—and sub-Saharan African countries generally—use much less fertilizer than many countries. With adoption of Bt maize and reduction in crop loss which increases yields, farmers may have more income that they choose to spend on fertilizer to apply to the crop; this could increase emissions and decrease the carbon benefits of adopting Bt maize. However, this does not mean that Kenyan farmers should not increase fertilizer use. For areas like sub-Saharan Africa where fertilizer use is below what is needed, increasing fertilizer application can raise yields and reduce land-use change enough to offset the increase in nitrous oxide emissions.[40]

In addition to reduced greenhouse gas emissions, reductions in pesticide use are a common environmental benefit associated with GM pest- and disease-resistant crops. GM insect-resistant maize reduced the environmental impact quotient (EIQ) of pesticide active ingredients by 0.09–60.9% in 7 countries from 1996–2020, with only the US and Brazil seeing reductions over 3% and Canada, Spain, South Africa, Colombia, and Vietnam seeing much lower reductions.[41] Though we did not estimate the reduction in the environmental impact quotient (EIQ) of pesticide use in Kenya due to adoption of Bt maize, the above range of historical reductions in different countries provides a reference for potential reductions in Kenya.

Both our analyses of economic and climate benefits assume that Kenya starting to grow more GM crops would have no effect on other countries' decisions to grow GM crops. However, if Kenya succeeds, it could encourage other countries especially within Africa to grow GM crops, or to start growing GM crops sooner. The economic benefits of GM crops realised by Kenya could motivate other countries to follow its lead. In addition, Kenya's development of locally adapted GM crop varieties could assist other countries' own research and development, thereby amplifying the climate mitigation impacts of Kenya's decision.

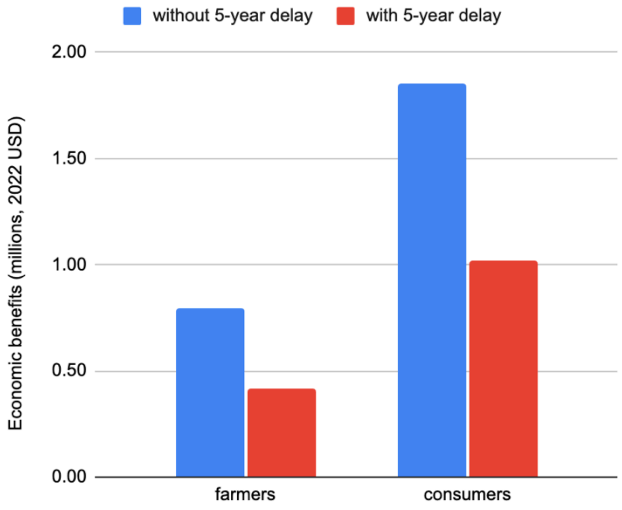
The economic and environmental benefits of Bt cotton in Kenya

In the sections below, we present the results drawn from the analysis of the potential economic and climate benefits of Bt cotton in Kenya, and the cost of delaying adoption. Our analysis uses a baseline of the current state of Kenya's cotton industry, including growth rates of cotton production and demand, which are both decreasing as the sector continues to decline. With further improvements to the sector in addition to commercialization of Bt cotton, the benefits could multiply.

Economic benefits of Bt cotton in Kenya

If Kenya had begun growing Bt cotton in 2015—when the technology could have been ready for commercialization without delays—Kenyan farmers and consumers could have gained an estimated USD 2.65 million in benefits by 2028 (medium scenario, Table 6; Appendix 4). Since there were at least 5 years of delay before the release of Bt cotton, farmers and consumers may only gain USD 1.44 million by 2033 (medium scenario, Table 6; Appendix 4). Therefore, 5 years of delay may have cost Kenyan farmers and consumers USD 1.21 million (Figure 4; Appendix 4).

Figure 4. Five years of delay in approval of genetically modified Bt cotton may have cost Kenyan farmers and consumers USD 1.21 million



Results presented are from the medium, most likely scenario. The cost of delay is the difference between the value of economic benefits without (blue) and with (red) regulatory delay in millions 2022 USD.

Though the estimated degree of economic benefits to Kenyan farmers and consumers varies widely between the low, medium, and high scenarios (Table 3), even in the low scenario with the smallest yield increase, cost decrease, and area grown with Bt cotton, adoption of Bt cotton would generate benefits for both farmers and consumers (Table 6).

Table 6. Kenyan farmers and consumers could gain USD 0.27–6.89 million in economic benefits from Bt cotton

Scenario	Delay?	Benefits to farmers	Benefits to consumers	Total benefits	Costs	Benefits-Costs	Benefits/Costs	Internal Rate of Return
		(millions 2022 USD)						(%)
high	no	2.08	4.81	6.89	1.9	5.04	3.71	19.44
high	yes	1.10	2.57	3.67	1.9	1.82	1.98	14.03
medium	no	0.80	1.86	2.65	1.9	0.80	1.43	13.04
medium	yes	0.42	1.02	1.44	1.9	-0.42	0.78	9.20
low	no	0.15	0.34	0.49	1.9	-1.36	0.27	1.50
low	yes	0.08	0.19	0.27	1.9	-1.59	0.14	0.41

Benefits presented here are the present value of the change in producer and consumer surplus due to adoption of technology, in millions 2022 USD. The present value of R&D costs is 1.9 million in 2022 USD in these scenarios, or 0.49 million in 2001 USD (Appendix 4).

The benefits of developing Bt cotton outweigh the costs in most scenarios, indicating that the investment from the international community and Kenyan government has been worthwhile. For all scenarios—low, medium, and high—the internal rate of return is between 0.4% and 20%. In the high scenarios with and without delay, and in the medium scenario without delay, the internal rates of return are above the discount rate of 10%; in addition, the benefit-cost ratios for these three scenarios are all over 1, suggesting that the investment has been worthwhile (Table 6; Appendix 4). In the low scenario—which reflects a situation in which seed systems fail to reach a majority of Kenyan farmers with Bt cotton—and in the medium scenario with delay, the internal rate of return is below the discount rate of 10% and the benefit-cost ratios are under 1, suggesting the investment has not been proven worthwhile (Table 6; Appendix 4).

Considering that cotton is currently grown on such a small area in Kenya compared to the potential, and that production has been shrinking for years, an expansion of cultivation could make past investment in Bt cotton worthwhile even in the low scenario where the percentage of farmers adopting the technology is low.

The above estimates of economic benefits do not include the potential benefits of reduced cotton imports. Kenya has strong garment manufacturing capacity,[12] but the country doesn't produce enough cotton lint for its textile; imports from Tanzania and Uganda fill the shortage.[13] If Kenya had started growing Bt cotton in 2015, then in 2023—when the technology would have spread to more farmers—the country could have produced 650 tons more domestic cotton (Appendix 16). In 2022, Kenya imported the equivalent of 5644 tons of seed cotton (3725 tons of cotton seed and 1155 tons of cotton lint; 2022 most recent year with data available on FAOSTAT). By producing 650 tons more domestic seed cotton, Kenya could replace 12% of imports received in 2022 (most recent year with data available on FAOSTAT).

Compared to the rest of East Africa, Kenya's total cotton production as well as cotton yields were much lower than Ethiopia, Uganda, or Tanzania from 2017–2019 (data from FAOSTAT). Among these East African countries in 2017, Kenya and Tanzania had much lower yields than Ethiopia and Uganda, but Kenya's yields were over 40% higher than Tanzania. However, in 2018 Kenya's cotton yields were 53% lower than Tanzania's cotton yields, and in 2019 they were 88% lower (author's calculations using data from FAOSTAT). If Kenya had grown Bt cotton in 2018 with a 15–40% yield increase (our low and high scenarios), the country could have substantially decreased the yield gap with Tanzania—yields could have been only 9–33% lower than Tanzania's in 2018, and 35–64% lower in 2019 (author's calculations using data from FAOSTAT).

Sensitivity analysis on the economic benefits of Bt cotton

To test the robustness of our results from the medium scenario, we vary additional inputs to the DREAMpy model including supply elasticity, supply and demand growth rates, adoption lag, and discount rate (values for sensitivity analysis are listed in Appendix 3). These sensitivity analyses involve varying inputs in the medium scenario that do not otherwise change between the low, medium, and high scenarios. Results of all sensitivity analyses are listed in Appendix 4.

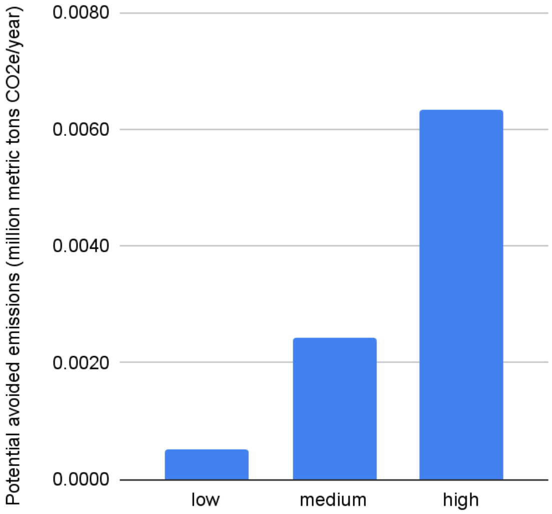
All the sensitivity analyses are based on the medium scenario, and though the total economic benefits increase or decrease, our results still suggest that past investment in Bt cotton in Kenya is worthwhile in the medium scenarios without delay—meaning the internal rate of return (IRR) remains above the discount rate, and the benefit-cost ratio remains over 1 (Appendix 4). However, in the medium scenarios with delay, most of the sensitivity analysis results suggest—like the main medium scenario—that past investments in Bt cotton have not yet been proven worthwhile. The only sensitivity analysis results for the medium scenario with delay that suggest the investment is worthwhile are those with a lower discount rate or lower supply elasticity.

For example, when we increase the adoption lag from 9 to 12 years, it takes longer for adoption of Bt maize to generate benefits for farmers and consumers, meaning the total benefits accumulated over the simulation period are lower; decreasing the adoption lag from 9 to 7 years does the opposite (Appendix 4). Changing the discount rate essentially decreases the impact that time has on the value of money, meaning that the cost of a 5-year delay also decreases (Appendix 4).

Environmental benefits of Bt cotton in Kenya

The results indicate that if Kenya grew Bt cotton in 2019, global greenhouse gas emissions could have decreased by 0.0005–0.0063 million metric tons of CO_2 equivalents per year (Figure 5). The different estimates for the low, medium, and high scenarios are due to both the degree of yield increase from the Bt trait in cotton and the extent of cotton cultivation area grown with Bt varieties.

Figure 5. Growing Bt cotton in Kenya could decrease global GHG emissions by 0.0005–0.0063 million tons CO_2e/year



Land use change emissions are calculated using the carbon opportunity cost approach. All calculations conducted using the Carbon Benefits Calculator v1.0.[36]

The emissions reductions in all scenarios are due to avoided emissions from deforestation (Figure 5). By increasing yields, adoption of GM cotton reduces the emissions intensity of cotton production in Kenya. Kenya—and sub-Saharan African countries generally—use much less fertiliser than many countries. With adoption of Bt cotton and reduction in crop loss which increases yields, farmers may have more income that they choose to spend on fertiliser to apply to the cotton crop; this could increase emissions and decrease the carbon benefits of adopting Bt cotton. However, this does not mean that Kenyan farmers should not increase fertiliser use. For areas like sub-Saharan Africa where fertiliser use is below what is needed, increasing fertiliser application can raise yields and reduce land-use change enough to offset the increase in nitrous oxide emissions.[40]

In addition to reduced greenhouse gas emissions, reductions in pesticide use are a common environmental benefit associated with GM pest- and disease-resistant crops. GM insect-resistant cotton reduced the environmental impact quotient (EIQ) of pesticide active ingredients by 9.8–63% in 9 countries from 1996–2020, with Mexico and the US seeing the smallest reductions (about 10–17%) and Colombia and India seeing the highest (about 46–63%).[42] Though we did not estimate the reduction in the environmental impact quotient (EIQ) of pesticide use in Kenya due to adoption of Bt cotton, the above range of historical reductions in different countries provides a reference for potential reductions in Kenya.

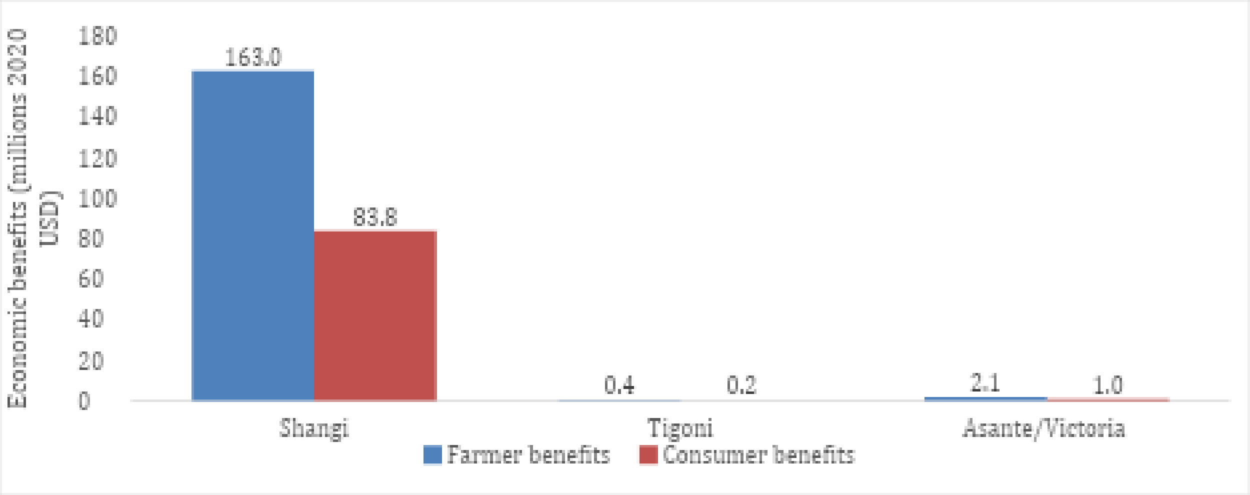
The economic and environmental benefits of 3R-gene potato in Kenya

This section presents the results of our analysis of the potential economic and climate benefits of the 3R-gene potato in Kenya, and the cost of delaying adoption. Our analysis uses a baseline of the current state of Kenya's potato production, including growth rates of potato production and demand, and we estimate potential yield increases and adoption rates of the 3R-genes.

Economic benefits of 3R-gene potato in Kenya

The assessment of the three potato varieties demonstrated that if Kenya was to pursue the release of one variety of GM potato, then the 3R-gene Shangi potato technology should be prioritized with the highest potential benefits (Figure 6; Appendix 6).

Figure 6. Potential economic benefits of 3R-gene potato varieties to farmers and consumers



Benefits presented here are the present value of the change in producer and consumer surplus due to adoption of technology in millions 2020 USD, and are for the most likely adoption scenario.

The release and commercialization of the 3R-gene Shangi potato variety would lead to an increase in producer and consumer benefits by USD 163 million and 83.8 million respectively, over a period of 30 years (30 years spread over eight years of research and development and 22 years of release in the market).

Farmers are likely to receive twice as many benefits as consumers are. Assessing the distribution of 3R-gene Shangi benefits across various production regions shows higher benefits likely to accrue to the South Rift Region, a high late blight-prone area where the possible adoption rates of the technology were highest.

Table 7. Economic benefits of 3R-gene Shangi potato variety across major production regions and late blight management practices in Kenya

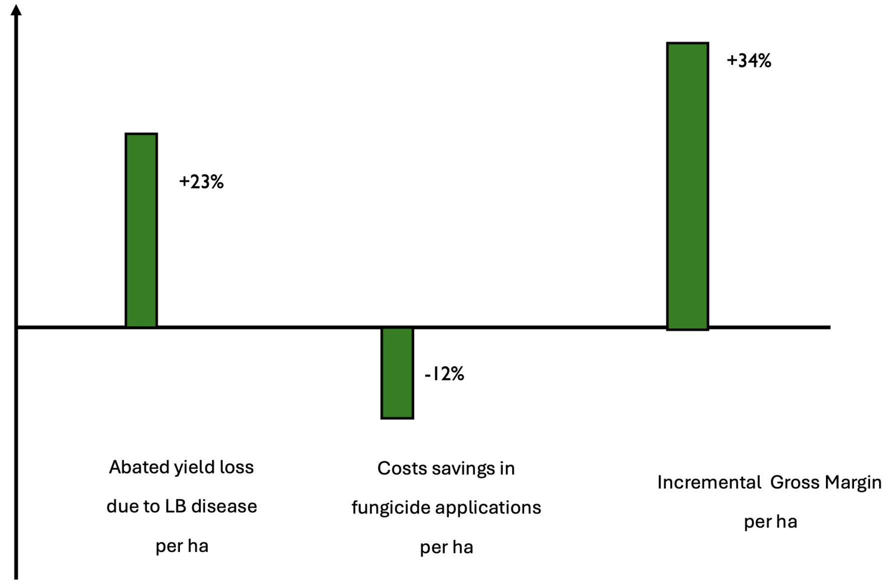
		Benefits to farmers	Benefits to consumers	Total benefits	Benefits-Costs	Benefits/Costs	Internal Rate of Return (%)
No spraying Fungicide Application	Eastern and Central Region	4.42	2.84	7.26	7.23	188.21	83
	North Rift Region	3.22	2.55	5.77	5.73	168.04	78
	South Rift Region	7.33	2.00	9.34	9.29	217.20	76
	Total	**14.97**	**7.39**	**22.37**	**22.25**	**192.99**	**79**
Tri-Weekly Fungicide Application	Eastern and Central Region	6.86	12.16	19.03	18.85	109.54	74
	North Rift Region	1.62	2.97	4.59	4.54	97.14	69
	South Rift Region	43.26	11.43	54.69	54.51	311.04	83
	Total	**51.74**	**26.57**	**78.30**	**77.90**	**197.37**	**78**
Bi-Weekly Fungicide Application	Eastern and Central Region	(2.38)	19.30	16.92	16.75	97.41	73
	North Rift Region	(3.27)	8.63	5.37	5.29	69.50	64
	South Rift Region	95.61	18.77	114.38	114.22	714.02	98
	Total	**89.97**	**46.71**	**136.67**	**136.26**	**332.43**	**86**
Weekly Fungicide Application	Eastern and Central Region	-	-	-	-	--.--	--.--
	North Rift Region	(0.01)	1.62	1.61	1.59	124.78	74
	South Rift Region	6.35	1.55	7.90	7.89	673.72	97
	Total	**6.33**	**3.17**	**9.50**	**9.48**	**386.39**	**88**

	Overall Total	**163.01**	**83.84**	**246.84**	**245.90**	**260.29**	

Benefits presented here are the present value of the change in producer and consumer surplus due to adoption of technology in millions 2020 USD, and are for the most likely adoption scenario.

At the farm level, in the event that a smallholder farmer adopts the 3R-gene Shangi potato variety, their profit is likely to increase by 34% compared to when growing the conventional Shangi variety.

Figure 7. Economic benefits to a 3R-gene Shangi potato smallholder farmer in Kenya

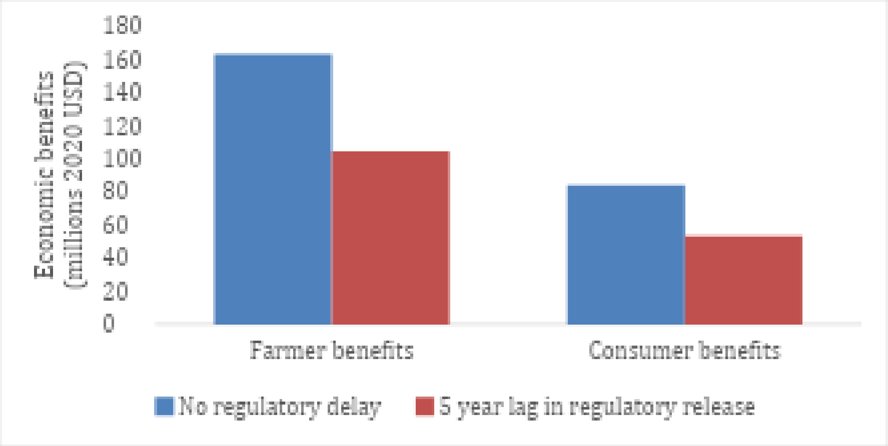


Results presented here are for the most likely adoption scenario.

Cost of delays to commercialization of 3R-gene potato in Kenya

With a base year of 2020 and a research and development phase of 8 years, Kenyan potato farmers and consumers would be able to realize estimated additional benefits of USD 163.01 million and USD 83.84 million respectively by 2049 if the technology is released in 2028 (Figure 8; Table 7). A 5 year lag in the release of the 3R-gene Shangi would reduce the benefits to farmers and consumers to USD 104.31 million and USD 53.34 million respectively.

Figure 8. Estimated cost of a 5-year delay in release of the 3R-gene Shangi potato variety in Kenya



Benefits presented here are the present value of the change in producer and consumer surplus due to adoption of technology in millions 2020 USD, and are for the most likely adoption scenario.

While the economic benefits vary across farmers with different late blight management practices (Table 7) and across regions (Appendix 7), regulatory delays are likely to significantly reduce benefits for both groups (Table 8). Although a regulatory release would have a negative impact on the potential benefits, the high internal rate of return, above the discount rate of 11.5 %, shows that a delay in the release of the 3R-gene Shangi does not alter the potential benefits of the technology.

Table 8. Estimated cost of a 5-year delay in release of the 3R-gene Shangi potato variety in Kenya

		Benefits to farmers	Benefits to consumers	Total benefits	Benefits-Costs	Benefits/Costs	Internal Rate of Return (%)
No spraying Fungicide Application	No regulatory delay	14.97	7.39	22.37	22.25	192.99	79
No spraying Fungicide Application	5 year Lag	9.8	4.81	14.61	14.5	126.08	50
Tri-Weekly Fungicide Application	No regulatory delay	51.74	26.57	78.3	77.9	197.37	78
Tri-Weekly Fungicide Application	5 year Lag	33.44	17.04	50.49	50.09	127.26	50
Bi-Weekly Fungicide Application	No regulatory delay	89.97	46.71	136.67	136.26	332.43	86
Bi-Weekly Fungicide Application	5 year Lag	57.13	29.51	86.64	86.23	210.73	54
Weekly Fungicide Application	No regulatory delay	6.33	3.17	9.5	9.48	386.39	88
Weekly Fungicide Application	5 year Lag	3.94	1.97	5.91	5.88	240.12	56

Benefits presented here are the present value of the change in producer and consumer surplus due to adoption of technology in millions 2020 USD, and are for the most likely adoption scenario.

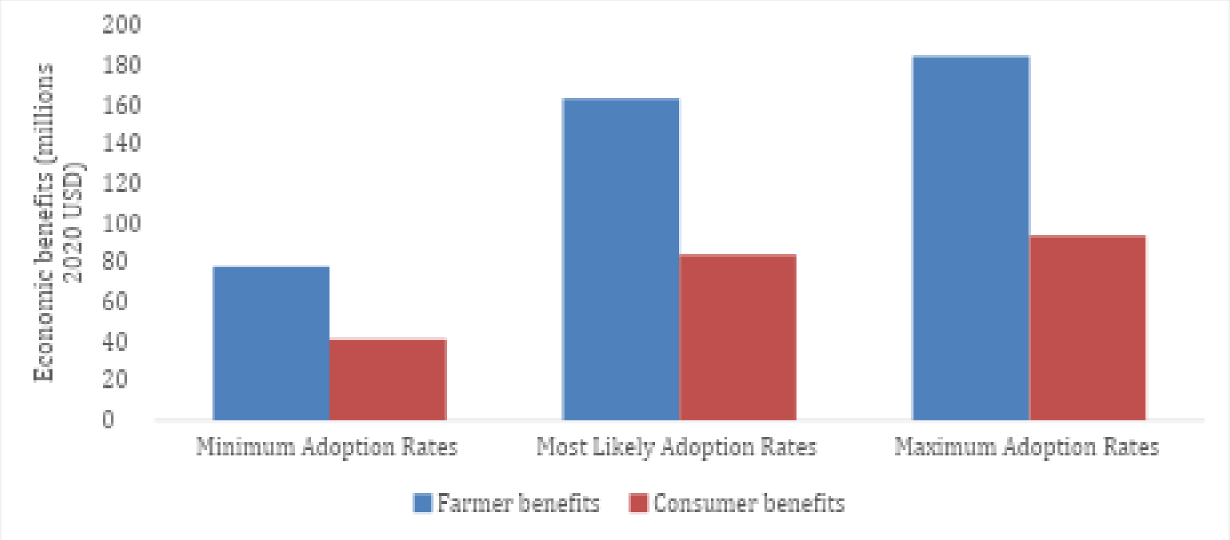
Sensitivity analysis for the economic benefits of GM potato

It is important to acknowledge that economic surplus model (ESM) applied in the analysis is sensitive to changes in key parameters, particularly technology adoption, yield, and cost reductions that determine the supply curve shifts.[27,33,43] To assess the robustness of the benefits assessed, we assess the plausible lowest economic benefits by varying the: (1) the adoption rates; (2) expected yield changes; (3) R&D costs; and (4) continued use of fungicides/ per unit cost reduction.

Maximum and minimum adoption level

Potential benefits were assessed for three adoption scenarios: minimum, most likely, and maximum adoption rates. Although the estimated economic benefits vary across the three scenarios, the results indicate that technology is a worthwhile investment. Under the minimum adoption rate, both farmers and consumers would still obtain over USD 100 million in incremental benefits by 2049 (Figure 9).

Figure 9. Present value of R&D benefits with maximum and minimum adoption levels for 3R-gene Shangi potato variety

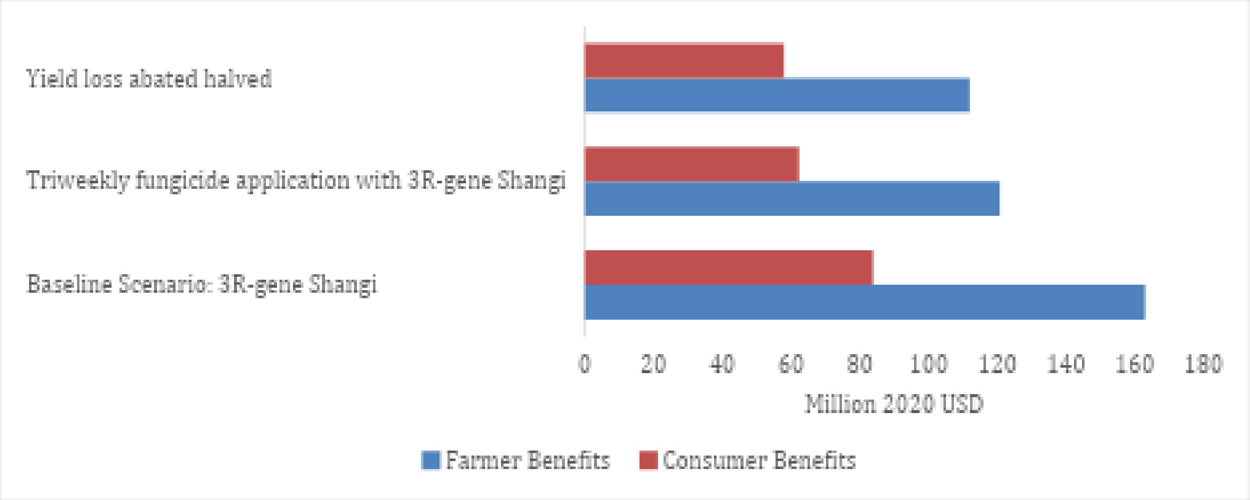


In addition, the importance of the technology is further demonstrated by the high internal rate of return for all the scenarios, which are above the discount rate of 11.5 % and the high cost-benefit ratios (Appendix 8).

Avoided yield losses halved

To assess the lowest plausible benefits of the anticipated productivity effects, we reduced the yield estimates by experts by half. The reduction in expected yield gains will reduce farmers' economic benefits from USD 163 million to 112 million and consumers' economic benefits from USD 83.8 million to 57.9 million (Figure 10; Appendix 9). Despite the reduced benefits, the significant benefit of the technology shows its importance in the potato subsector in the country.

Figure 10. Potential economic benefits of 3R-gene Shangi potato variety to farmers and consumers in baseline scenario vs triweekly fungicide application and lower yield loss



Benefits presented here are the present value of the change in producer and consumer surplus due to adoption of technology in millions 2020 USD, and are for the most likely adoption scenario.

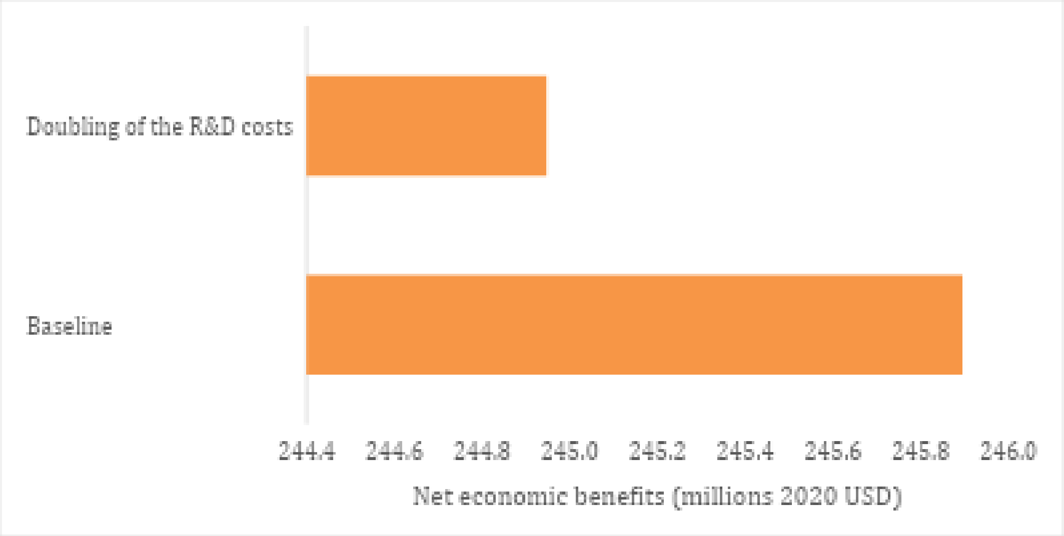
Continued use of fungicides

Although confined field trials indicate that the 3R-gene technology is completely resistant to late blight disease, requiring no fungicide spray, it is expected that some farmers would continue to apply fungicides as they observe the performance of the technology. Thus, we assumed that all farmers currently apply fungicides to continue applying fungicides on a tri-weekly basis during the cropping season. The resulting benefits show that though the farmers and consumers benefits reduce to USD 120.7 million and USD 62.3 million respectively, the technology would still be highly beneficial (Figure 10; Appendix 11).

Doubling of R&D costs

The results (Figure 11 and Appendix 10) demonstrate that investments in 3R-gene technology are worthwhile, even with doubling research costs.

Figure 11. Net economic benefits of 3R-gene Shangi potato variety with doubling of R&D costs vs baseline



Benefits presented here are the net present value of the change in producer and consumer surplus due to adoption of technology in millions 2020 USD, and are for the most likely adoption scenario.

Overall, the sensitivity analysis underscores the importance of technology, even under the least favourable parameter variations.

Environmental benefits of 3R-gene potato in Kenya

We did not estimate the potential for GM late blight disease-resistant potato to reduce global greenhouse gas emissions because the crop is used almost solely as subsistence in Kenya, and therefore is not part of global agricultural trade that impacts global emissions. Besides reduced greenhouse gas emissions, reductions in pesticide use are a common environmental benefit associated with GM pest- and disease-resistant crops. The 3R-gene Shangi potato variety is completely resistant to late blight and requires no fungicide sprays. Without being able to grow a blight-resistant variety, Kenyan farmers spray their potato crops with fungicide up to once a week to control the late blight disease.

Conclusions and call for action

Overall, the results from the current study show that growing Bt maize, Bt cotton, and 3R-gene potato in Kenya could create substantial economic and environmental benefits. Even under scenarios with the lowest yield increase and adoption of Bt maize and 3R-gene potato in Kenya, we estimate that both would still have significant benefits for farmers and consumers. The adoption of the technology is expected to benefit producers through the increase in yields/productivity which translates to more output and income. Also, consumers stand to benefit from lower food prices and safer food products as a result of reduced exposure to pesticides. Although lower food prices may imply producers' welfare will be reduced, it is imperative to note that the increase in consumer welfare as a result of lower food prices is large enough to compensate for the loss in producer welfare as a result of lower producer prices associated with increased supply. Further, farmers benefit from higher revenue associated with more production.

Kenyan farmers that can potentially grow Bt maize, Bt cotton, or 3R-gene potato may benefit from higher yields and increased production by having more harvest for their family to consume, selling more, or spending less money and time on buying and spraying pesticides and fungicides. The types of benefits to farmers from Bt maize and Bt potato depend on whether their current production is all for consumption, whether they already sell some of their harvest, and how much they currently spray pesticides or fungicides. For example, farmers that do not spray pesticides or fungicides often may benefit more from a yield increase while farmers that use pesticides or fungicides effectively may see less yield increase but benefit from a decrease in expenses from chemicals. Due to data limitations for Bt maize and Bt cotton, we estimated benefits for the country rather than by district or agro-ecological zone. However, the benefits will vary within the country based on the agro ecological zones where each crop is grown and the distribution of pests and disease. Our estimates of the benefits are the total for all farmers in Kenya, but some farmers will benefit more than others.

As expected, Kenyan consumers primarily benefit from lower prices for food and goods, which enable them to consume more at a lower price or consume the same amount with lower costs. Maize forms a large part of Kenyan diets in the form of ugali, and a small proportion of the country's total consumption is used for animal feed. Potatoes are the second most important food crop in Kenya after maize. Reduced pesticide use could also improve consumer and farmer health, which we did not estimate here. Based on the potential reduction in global GHG emissions from Kenya's increased maize and cotton yields, Kenya benefits by contributing to global emissions mitigation and everyone benefits from potential reductions in deforestation, habitat and biodiversity loss, and global climate change.

Given the results from this study, we identify critical actions that will drive the biotech development forward and create benefits for farmers and consumers.

- Kenya should prioritise commercialization of new varieties of Bt maize that could increase the yield benefits of GM maize cultivation. We estimate the potential economic impact of yield increases in maize due to adoption of the MON810 Bt trait in TELA maize varieties currently ready for release in Kenya. The adoption of the available varieties will pave the way for future products that will have additional benefits. Updated varieties of TELA maize are currently in development that have a different Bt gene (MON89034) that in addition to stem borer protection also provides good protection against fall armyworm, which is a very damaging maize pest in Kenya. Finally, some updated varieties of TELA in development also have a genetically modified trait for additional drought tolerance (MON87460), which could improve upon the current TELA variety's conventionally bred drought tolerant genome.
- To increase Kenya's benefit from Bt cotton, the country should continue Bt cotton demonstrations to improve farmer awareness; increase the capacity for local and regional seed production; ensure farmers have the option to purchase seed from multiple sources; forming Public Private Partnerships to help meet seed demand; and improving farmer access to markets.[8] In addition, considering that both hybrid cotton is generally a new technology for most Kenyan farmers, in addition to Bt hybrid cotton specifically, county governments could make county clusters to help farmers get seed, inputs, and access to

markets; and extension services could help train farmers on the agronomic needs of hybrid cotton varieties generally.[44]

- Though removing barriers like the import ban is crucial to increase Kenya's benefits from GM crops, the country must also increase support for agricultural research, development, and extension to improve agricultural performance using many technologies,[45] including GM. The ban on GM crops in Kenya from 2012–2022 negatively impacted the country in many ways, including decreasing access to affordable feed for livestock; contributing to a decline in funding for biotechnology research and in university students studying biotechnology; and denying Kenya business in transport and handling cargo due to the ban on transit of GM products. Research accounting for these other factors, which were outside the scope of this report, would also be helpful to give a more complete picture of the impacts of GM crops in Kenya.

Author contributions

Mark Lynas, Sheila Ochugboju, Emma Kovak, Vitumbiko Chinoko, Verenardo Meeme, Edna Macharia, Akefetey Ephraim, Fiona Mosongo, and Michael Onyango designed the project during a two-day workshop. Emma Kovak developed the methodology, conducted the research and analysis, and wrote most of the report for maize and cotton. Evelyne Kihiu developed the methodology, conducted the research and analysis, and wrote the potato sections of the report. Mark Lynas wrote the general introduction, Verenardo Meeme wrote introductory material about TELA maize and the role of biotechnology in Africa, and Edna Macharia wrote introductory material about Bt cotton and the court cases. Akefetey Ephraim, Edna Macharia, Verenardo Meeme, Daniel Willy, and Mark Lynas commented and edited the draft report. Wenceslao Almazán designed the report. All authors approved the final report.

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Appendices

Appendix 1. Input values for analysis of economic benefits of Bt maize in Kenya using the DREAMpy model.

Parameter	Unit	Values for low, medium, and high scenarios	Values for sensitivity analysis	Source
VALUES FOR KENYA REGION				
Base year	year	2000	-	expert consultation
simulation period	years	30 no delay, 35 with delay	-	sum of R&D and regulatory lag and adoption lag, with or without 5-year regulatory delay; roughly 30-year planning horizon; total simulation length extended by 5 years when 5-year regulatory delay added
real discount rate	percentage	10%	5%	[46] [47]
initial price	million USD/1000T	0.1856	-	FAOSTAT, producer price
elasticity of supply	neutral	0.68	0.8	[5,48]
elasticity of demand	neutral	-0.40	-	[48]
exogenous supply growth rate	percentage	1.99%	1.59%, 2.39%	author's calculations of average yearly percent change from 2000 to 2019, from FAOSTAT data on total maize production
exogenous demand growth rate	percentage	2.32%	1.86%, 2.78%	author's calculations of average yearly percent change from 2000 to 2019, from USDA data on total maize consumption
production quantity	1000T	2424	-	FAOSTAT
consumption quantity	1000T	2687	-	[49]
taxes or subsidies to production	percentage	none	none	too variable during period of analysis to include
taxes or subsidies to consumption	percentage	none	none	too variable during period of analysis to include
R&D and regulatory time lag	years	19 no delay, 24 with delay	-	expert consultation
probability R&D and regulatory success	percentage	100	-	Bt maize is already ready for commercialization in Kenya
maximum adoption rate	percentage	40, 60, 72	20	literature and expert consultation
time to maximum adoption	years	6	4, 8	literature and expert consultation
yield change with technology	percentage	7.4, 10.2, 15.6	-	literature and expert consultation
cost change with technology	percentage	6.1, -1.0, -4.5	-	[50,51]
cost of extension and technology (total)	million USD	4.75	-	literature and expert consultation
VALUES FOR "Rest of World" REGION				
Initial price	million USD/1000T	0.1856	-	same as for Kenya region
production quantity	1000T	263	-	balance region, accounts for difference between Kenya's production and consumption
supply elasticity	neutral	0.68	-	same as for Kenya region
production growth rate	percentage	1.99%	1.59%, 2.39%	same as for Kenya region
consumption quantity	1000T	0	-	balance region, only accounts for difference between Kenya's production and consumption

demand elasticity	neutral	0	-	balance region, only accounts for difference between Kenya's production and consumption
consumption growth rate	percentage	0	-	balance region, only accounts for difference between Kenya's production and consumption
probability R&D and regulatory success	percentage	100	-	doesn't affect results because this region does not adopt the technology

USD values presented are in millions 2000 USD to match the base year. For cost of extension and technology, all USD values were converted from the year when funding began to USD for the base year 2000.

Appendix 2. Output from analysis of economic benefits of Bt maize in Kenya using the DREAMpy model, including sensitivity analysis results.

	Δ Farmer Surplus	**Δ Consumer Surplus**	**Δ Total Surplus**	**Costs**	**Δ B-Δ C**	**Δ B/Δ C**	**IRR**
	million USD, real 2001 value						%
high, no delay	46.77	67.81	114.57	2.16	112.42	53.15	33.84
high, yes delay	32.36	46.93	79.29	2.16	77.13	36.78	27.15
medium, no delay	22.84	33.2	56.03	2.16	53.88	25.99	29.43
medium, yes delay	15.8	22.98	38.78	2.16	36.63	17.99	23.73
low, no delay	4.93	7.19	12.12	2.16	9.97	5.62	20.39
low, yes delay	3.42	4.98	8.39	2.16	6.24	3.89	16.62
medium, no delay, supply elasticity high	18.13	30.24	48.38	2.16	46.22	22.44	28.54
medium, no delay, demand and supply growth rates low	20.54	29.86	50.4	2.16	48.24	23.38	28.82
medium, no delay, demand and supply growth rates high	25.38	36.9	62.28	2.16	60.12	28.89	30.05
medium, no delay, adoption lag 8	19.51	28.36	47.87	2.16	45.71	22.21	28.01
medium, no delay, adoption lag 4	26.26	38.17	64.42	2.16	62.27	29.88	30.88
medium, no delay, discount rate 5	76.19	110.76	186.95	2.95	184	63.36	29.43
medium, yes delay, supply elasticity high	12.56	20.95	33.5	2.16	31.35	15.54	23.04
medium, yes delay, demand and supply growth rates low	13.91	20.23	34.14	2.16	31.98	15.84	23.14
medium, yes delay, demand and supply growth rates high	17.94	26.09	44.03	2.16	41.88	20.43	24.32
medium, yes delay, adoption lag 8	13.5	19.63	33.13	2.16	30.98	15.37	22.72
medium, yes delay, adoption lag 4	18.17	26.41	44.59	2.16	42.43	20.68	24.72
medium, yes delay, discount rate 5	66.54	96.73	163.27	2.95	160.32	55.34	23.73
low, no delay, 20% adoption	2.46	3.59	6.05	2.16	3.9	2.81	16.42
low, yes delay, 20% adoption	1.58	2.31	3.89	2.16	1.74	1.8	13.12

Δ B-Δ C means the change in benefits minus the change in costs and is otherwise known as the net benefits. Δ B/Δ C means the change in benefits divided by the change in costs.

Appendix 3. Input values for analysis of economic benefits of Bt cotton in Kenya using the DREAMpy model.

Parameter	Unit	Values for low, medium, and high scenarios	Values for sensitivity analysis	Source
VALUES FOR KENYA REGION				
Base year	year	2001	-	[52]
simulation period	years	28 no delay, 33 with delay	-	sum of R&D and regulatory lag and adoption lag, with or without 5-year regulatory delay; roughly 30-year planning horizon; total simulation length extended by 5 years when 5-year regulatory delay added
real discount rate	percentage	10%	5%	[46] [47]
initial price	million USD/1000T	0.2332	-	FAOSTAT, producer price
elasticity of supply	neutral	1	0.3	[25]
elasticity of demand	neutral	-0.06	-	[25]
exogenous production growth rate	percentage	-4.35%	-5.22%, -3.48%	author's calculations of average yearly percent change from 2001 to 2019, from FAOSTAT data on total cotton production
exogenous consumption growth rate	percentage	-2.68%	-3.22%, -2.15%	author's calculations of average yearly percent change from 2001 to 2022 using data from Index Mundi
production quantity	1000T	22	-	FAOSTAT
consumption quantity	1000T	34	-	[53]
taxes or subsidies to production	percentage	none	none	too variable during period of analysis to include
taxes or subsidies to consumption	percentage	none	none	too variable during period of analysis to include
R&D and regulatory time lag	years	14 no delay, 19 with delay	-	authors' analysis of literature and regulatory timeline
probability R&D and regulatory success	percentage	100	-	Bt cotton is already commercialized in Kenya
maximum adoption rate	percentage	20, 70, 90	-	[25]
time to maximum adoption	years	9	7, 12	[25]
yield change with technology	percentage	15, 20, 40	-	[25]
cost change with technology	percentage	0.4, -4.6, -10.2	-	[52], [25]
cost of extension and technology (total)	million USD	0.85	-	[25]
VALUES FOR "Rest of World" REGION				
Initial price	million USD/1000T	0.2332	-	same as for Kenya region
production quantity	1000T	12	-	balance region, accounts for difference between Kenya's production and consumption
elasticity of supply	neutral	1	0.3	same as for Kenya region
exogenous supply growth rate	percentage	-4.35%	-5.22%, -3.48%	same as for Kenya region
consumption quantity	1000T	0	-	balance region, only accounts for difference between Kenya's production and consumption
elasticity of demand	neutral	0	-	balance region, only accounts for difference between Kenya's production and consumption

exogenous demand growth rate	percentage	0	-	balance region, only accounts for difference between Kenya's production and consumption
probability R&D and regulatory success	percentage	100	-	doesn't affect results because this region does not adopt the technology

USD values presented are in millions 2000 USD to match the base year. For cost of extension and technology, all USD values were converted from the year when funding began to USD for the base year 2000.

Appendix 4. Output from analysis of economic benefits of Bt cotton in Kenya using the DREAMpy model, including sensitivity analysis results.

	Δ Farmer Surplus	**Δ Consumer Surplus**	**Δ Total Surplus**	**Costs**	**Δ B-Δ C**	**Δ B/Δ C**	**IRR**
	million USD, real 2001 value						%
high, no delay	0.55	1.27	1.81	0.49	1.33	3.71	19.44
high, yes delay	0.29	0.68	0.98	0.49	0.49	2	14.03
medium, no delay	0.21	0.49	0.7	0.49	0.21	1.44	13.04
medium, yes delay	0.11	0.27	0.38	0.49	-0.11	0.78	9.2
low, no delay	0.04	0.09	0.12	0.49	-0.37	0.25	1.5
low, yes delay	0.02	0.05	0.07	0.49	-0.42	0.14	0.41
medium, no delay, supply elasticity low	0.69	1.24	1.94	0.49	1.45	3.97	19.91
medium, no delay, demand and supply growth rates low	0.18	0.44	0.62	0.49	0.13	1.27	12.23
medium, no delay, demand and supply growth rates high	0.23	0.56	0.79	0.49	0.3	1.62	13.83
medium, no delay, adoption lag 7	0.24	0.58	0.82	0.49	0.34	1.69	14.24
medium, no delay, adoption lag 12	0.16	0.38	0.54	0.49	0.06	1.11	11.29
medium, no delay, discount rate 5	0.59	1.41	2	0.62	1.38	3.23	13.04
medium, yes delay, supply elasticity low	0.37	0.66	1.03	0.49	0.55	2.12	14.33
medium, yes delay, demand and supply growth rates low	0.1	0.23	0.33	0.49	-0.16	0.67	8.43
medium, yes delay, demand and supply growth rates high	0.13	0.31	0.44	0.49	-0.05	0.9	9.95
medium, yes delay, adoption lag 7	0.13	0.31	0.44	0.49	-0.04	0.91	10
medium, yes delay, adoption lag 12	0.09	0.21	0.29	0.49	-0.19	0.6	7.98
medium, yes delay, discount rate 5	0.4	0.96	1.36	0.62	0.74	2.19	9.2

Red highlight indicates values for benefit/cost ratio under 1 and values for internal rate of return (IRR) under the discount rate (10% for all scenarios not specified, 5% when specified). Δ B-Δ C means the change in benefits minus the change in costs and is otherwise known as the net benefits. Δ B/Δ C means the change in benefits divided by the change in costs.

Appendix 5. Input values for analysis of economic benefits of 3R-gene Shangi potato variety in Kenya using the DREAMpy model.

Parameter	Unit	Values for most likely scenario	Values for sensitivity analysis	Source
base year	year	2020	-	Expert elicitation

simulation period	years	30 years	-	Based on adoption estimation curve i.e. Expected years to reach maximum adoption + Expected years at maximum adoption + Expected years to abandonment
real discount rate	percentage	11.5%	-	Economic Opportunity Cost of Capital (EOCK) (National Treasury, 2021)
Shangi initial price				
North rift	KES/1000T	32.14	23.57 to 39.29	Expert elicitation
South rift	KES/1000T	30.5	14 to 42.5	Expert elicitation
Central and Eastern Kenya	KES/1000T	37.5	22 to 61	Expert elicitation
elasticity of supply	neutral	0.596	-	[54]
elasticity of demand	neutral	−0.893	-	[55]
exogenous production growth rate	percentage	4.4	-	author's calculations of yearly percent change-average values of 2018 to 2020 taken
exogenous consumption growth rate	percentage	5.16	-	
production quantity				
Untreated - No LB fungicide sprayed in a cropping season				
North rift	1000T	75.50	-	Calculated using data from Data Source Kilimo: http://statistics.kilimo.go.ke/en/ and from experts' views of variety shares
South rift	1000T	46.87	-	
Central and Eastern Kenya	1000T	72.92	-	
Tri-weekly fungicide application (approximately 3 sprays per cropping season)				
North rift	1000T	114.20	-	Calculated using data from Data Source Kilimo: http://statistics.kilimo.go.ke/en/ and from experts' views of variety shares
South rift	1000T	404.76	-	
Central and Eastern Kenya	1000T	417.64	-	
Bi-weekly fungicide application (approximately 4 sprays per cropping season)				
North rift	1000T	203.86	-	Calculated using data from Data Source Kilimo: http://statistics.kilimo.go.ke/en/ and from experts' views of variety shares
South rift	1000T	543.47	-	
Central and Eastern Kenya	1000T	447.47	-	
Weekly fungicide application (approximately 7 sprays per cropping season)				
North rift	1000T	48.13	-	Calculated using data from Data Source Kilimo: http://statistics.kilimo.go.ke/en/ and from experts' views of variety shares
South rift	1000T	46.87	-	
Central and Eastern Kenya	1000T		-	Negligent number of farmers under this category from expert views
consumption quantity				
North rift	1000T	264.61	-	Calculated using national consumption data from AFA Year Book of Statistics 2022 and production shares. *Consumption shares are assumed to be similar to production shares (i.e of what is produced, how much is consumed?)
South rift	1000T	602.2	-	
Central and Eastern Kenya	1000T	594.81	-	
R&D and regulatory time lag	years	8 no delay	13 with delay	Based on [56]
probability R&D and regulatory success	percentage	90	-	Expert views
maximum adoption rate				
North rift	percentage	12	8 to 17	Expert elicitation
South rift	percentage	44	30 to 53	Expert elicitation
Central and Eastern Kenya	percentage	20	10 to 30	Expert elicitation
time to maximum adoption				
North rift	years	5	-	Expert elicitation
South rift	years	7	-	Expert elicitation
Central and Eastern Kenya	years	5	-	Expert elicitation
yield change with technology				
Untreated - No LB fungicide sprayed in a cropping season				
North rift	percentage	91.7	-	Expert elicitation

South rift	percentage	55	-	Expert elicitation
Central and Eastern Kenya	percentage	61.3	-	Expert elicitation
Tri-weekly fungicide application (approximately 3 sprays per cropping season)				
North rift	percentage	22.1	-	Expert elicitation
South rift	percentage	17.5	-	Expert elicitation
Central and Eastern Kenya	percentage	15	-	Expert elicitation
Bi-weekly fungicide application (approximately 4 sprays per cropping season)				
North rift	percentage	9.2	-	Expert elicitation
South rift	percentage	35	-	Expert elicitation
Central and Eastern Kenya	percentage	10	-	Expert elicitation
Weekly fungicide application (approximately 7 sprays per cropping season)				
North rift	percentage	0	-	Expert elicitation
South rift	percentage	0	-	Expert elicitation
Central and Eastern Kenya	percentage	0	-	Expert elicitation
cost change with technology				
Untreated - No LB fungicide sprayed in a cropping season				
North rift	percentage	0	-	Expert elicitation
South rift	percentage	0	-	Expert elicitation
Central and Eastern Kenya	percentage	0	-	Expert elicitation
Tri-weekly fungicide application (approximately 3 sprays per cropping season)				
North rift	percentage	-14	0	Expert elicitation
South rift	percentage	-13	0	Expert elicitation
Central and Eastern Kenya	percentage	-7	0	Expert elicitation
Bi-weekly fungicide application (approximately 4 sprays per cropping season)				
North rift	percentage	-17	-3	Expert elicitation
South rift	percentage	-18	-5	Expert elicitation
Central and Eastern Kenya	percentage	-9	-2	Expert elicitation
Weekly fungicide application (approximately 7 sprays per cropping season)				
North rift	percentage	-25	-12	Expert elicitation
South rift	percentage	-30	-20	Expert elicitation
Central and Eastern Kenya	percentage			Expert elicitation
research and development costs (total)	million USD	1.35	-	Based on [56]

Appendix 6. Potential economic benefits of 3R-gene potato varieties to farmers and consumers (present value of R&D benefits in millions 2020 USD).

		Δ Farmer Surplus	**Δ Consumer Surplus**	**Δ Total Surplus**	**Δ B-Δ C**	**Δ B/Δ C**	**IRR (%)**
Shangi	No spraying Fungicide Application	14.97	7.39	22.37	22.25	192.99	14.97
	Tri-Weekly Fungicide Application	51.74	26.57	78.30	77.90	197.37	51.74
	Bi-Weekly Fungicide Application	89.97	46.71	136.67	136.26	332.43	89.97
	Weekly Fungicide Application	6.33	3.17	9.50	9.48	386.39	6.33
	Overall Total	**163.01**	**83.84**	**246.84**	**245.90**	**260.29**	**163.01**
Tigoni	No spraying Fungicide Application	0.05	0.02	0.07	-0.06	0.54	0.05
	Tri-Weekly Fungicide Application	0.14	0.07	0.21	-0.17	0.55	0.14
	Bi-Weekly Fungicide Application	0.20	0.10	0.30	-0.13	0.70	0.20
	Weekly Fungicide Application	0.01	0.00	0.01	-0.01	0.52	0.01
	Overall Total	**0.39**	**0.19**	**0.58**	**-0.37**	**0.61**	**0.39**
Asante/Victoria	No spraying Fungicide Application	0.35	0.16	0.51	0.42	5.35	0.35
	Tri-Weekly Fungicide Application	0.88	0.41	1.29	0.86	3.03	0.88
	Bi-Weekly Fungicide Application	0.87	0.40	1.28	0.85	2.99	0.87
	Weekly Fungicide Application	0.00	0.00	0.00	0.00	0.53	0.00
	Overall Total	**2.10**	**0.97**	**3.08**	**2.13**	**3.25**	**2.10**

∆ B-∆ C means the change in benefits minus the change in costs and is otherwise known as the net benefits. ∆ B/∆ C means the change in benefits divided by the change in costs.

Appendix 7. Cost of Delays to commercialization of 3R-gene Shangi potato variety by region (present value of R&D benefits in millions 2020 USD).

			∆ Farmer Surplus	**∆ Consumer Surplus**	**∆ Total Surplus**	**∆ B-∆ C**	**∆ B/∆ C**	**IRR (%)**
No spraying Fungicide Application	No delay	Eastern and Central Region	4.42	2.84	7.26	7.23	188.21	83
	5 year Lag	Eastern and Central Region	3.39	1.85	5.24	5.20	135.71	52
	No delay	North Rift Region	3.22	2.55	5.77	5.73	168.04	78
	5 year Lag	North Rift Region	1.97	1.66	3.63	3.59	105.72	49
	No delay	South Rift Region	7.33	2.00	9.34	9.29	217.20	76
	5 year Lag	South Rift Region	4.45	1.30	5.75	5.70	133.70	49
	No delay	**Total**	**14.97**	**7.39**	**22.37**	**22.25**	**192.99**	**79**
	5 year Lag	**Total**	**9.80**	**4.81**	**14.61**	**14.50**	**126.08**	**50**
Tri-Weekly Fungicide Application	No delay	Eastern and Central Region	6.86	12.16	19.03	18.85	109.54	74
	5 year Lag	Eastern and Central Region	6.05	7.82	13.87	13.69	79.85	47
	No delay	North Rift Region	1.62	2.97	4.59	4.54	97.14	69
	5 year Lag	North Rift Region	0.98	1.90	2.89	2.84	61.18	44
	No delay	South Rift Region	43.26	11.43	54.69	54.51	311.04	83
	5 year Lag	South Rift Region	26.41	7.32	33.73	33.55	191.84	53
	No delay	**Total**	**51.74**	**26.57**	**78.30**	**77.90**	**197.37**	**78**
	5 year Lag	**Total**	**33.44**	**17.04**	**50.49**	**50.09**	**127.26**	**50**
Bi-Weekly Fungicide Application	No delay	Eastern and Central Region	-2.38	19.30	16.92	16.75	97.41	73
	5 year Lag	Eastern and Central Region	0.38	12.22	12.60	12.42	72.53	46
	No delay	North Rift Region	-3.27	8.63	5.37	5.29	69.50	64
	5 year Lag	North Rift Region	-2.06	5.45	3.39	3.31	43.90	41
	No delay	South Rift Region	95.61	18.77	114.38	114.22	714.02	98
	5 year Lag	South Rift Region	58.81	11.84	70.65	70.49	441.02	61
	No delay	**Total**	**89.97**	**46.71**	**136.67**	**136.26**	**332.43**	**86**
	5 year Lag	**Total**	**57.13**	**29.51**	**86.64**	**86.23**	**210.73**	**54**
Weekly Fungicide Application	No delay	Eastern and Central Region						
	5 year Lag	Eastern and Central Region						
	No delay	North Rift Region	-0.01	1.62	1.61	1.59	124.78	74
	5 year Lag	North Rift Region	0.02	1.01	1.02	1.01	79.39	47
	No delay	South Rift Region	6.35	1.55	7.90	7.89	673.72	97
	5 year Lag	South Rift Region	3.92	0.96	4.88	4.87	416.65	61
	No delay	**Total**	**6.33**	**3.17**	**9.50**	**9.48**	**386.39**	**88**
	5 year Lag	**Total**	**3.94**	**1.97**	**5.91**	**5.88**	**240.12**	**56**

∆ B-∆ C means the change in benefits minus the change in costs and is otherwise known as the net benefits. ∆ B/∆ C means the change in benefits divided by the change in costs.

Appendix 8. Potential economic benefits of 3R-gene potato varieties to farmers and consumers in scenarios with maximum and minimum adoption levels (present value of R&D benefits in millions 2020 USD).

			∆ Farmer Surplus	**∆ Consumer Surplus**	**∆ Total Surplus**	**∆ B-∆ C**	**∆ B/∆ C**	**IRR (%)**
No spraying Fungicide Application	Minimum Adoption Rates	Eastern and Central Region	1.18	1.18	2.35	2.31	60.94	77
	Most Likely Adoption Rates	Eastern and Central Region	4.42	2.84	7.26	7.23	188.21	83

	Maximum Adoption Rates	Eastern and Central Region						
	Minimum Adoption Rates	North Rift Region	0.56	1.06	1.62	1.58	47.11	73
	Most Likely Adoption Rates	North Rift Region	3.22	2.55	5.77	5.73	168.04	78
	Maximum Adoption Rates	North Rift Region	0.66	1.84	2.50	2.48	193.87	82
	Minimum Adoption Rates	South Rift Region	4.34	0.83	5.17	5.13	120.36	80
	Most Likely Adoption Rates	South Rift Region	7.33	2.00	9.34	9.29	217.20	76
	Maximum Adoption Rates	South Rift Region	6.54	1.75	8.30	8.29	707.97	89
	Minimum Adoption Rates	**Total**	**6.08**	**3.06**	**9.14**	**9.03**	**78.87**	**77**
	Most Likely Adoption Rates	**Total**	**14.97**	**7.39**	**22.37**	**22.25**	**192.99**	**79**
	Maximum Adoption Rates	**Total**	**7.20**	**3.59**	**10.79**	**10.77**	**438.87**	**86**
Tri-Weekly Fungicide Application	Minimum Adoption Rates	Eastern and Central Region	(0.07)	5.85	5.78	5.61	33.27	66
	Most Likely Adoption Rates	Eastern and Central Region	6.86	12.16	19.03	18.85	109.54	74
	Maximum Adoption Rates	Eastern and Central Region	17.92	14.77	32.69	32.52	188.23	75
	Minimum Adoption Rates	North Rift Region	(0.25)	1.43	1.18	1.13	24.93	63
	Most Likely Adoption Rates	North Rift Region	1.62	2.97	4.59	4.54	97.14	69
	Maximum Adoption Rates	North Rift Region	3.26	3.61	6.87	6.82	145.53	76
	Minimum Adoption Rates	South Rift Region	24.58	5.51	30.10	29.92	171.17	87
	Most Likely Adoption Rates	South Rift Region	43.26	11.43	54.69	54.51	311.04	83
	Maximum Adoption Rates	South Rift Region	43.16	13.88	57.04	56.87	324.42	**76**
	Minimum Adoption Rates	**Total**	**24.26**	**12.79**	**37.05**	**36.65**	**93.39**	**78**
	Most Likely Adoption Rates	**Total**	**51.74**	**26.57**	**78.30**	**77.90**	**197.37**	**78**
	Maximum Adoption Rates	**Total**	**64.35**	**32.26**	**96.61**	**96.21**	**243.51**	**75**
Bi-Weekly Fungicide Application	Minimum Adoption Rates	Eastern and Central Region	(5.17)	9.72	4.55	4.38	26.22	64
	Most Likely Adoption Rates	Eastern and Central Region	(2.38)	19.30	16.92	16.75	97.41	73
	Maximum Adoption Rates	Eastern and Central Region	8.30	22.29	30.59	30.41	176.10	74
	Minimum Adoption Rates	North Rift Region	(3.39)	4.36	0.97	0.89	12.52	55
	Most Likely Adoption Rates	North Rift Region	(3.27)	8.63	5.37	5.29	69.50	64
	Maximum Adoption Rates	North Rift Region	(1.32)	9.97	8.65	8.57	111.96	73
	Minimum Adoption Rates	South Rift Region	52.90	9.47	62.37	62.21	389.33	105
	Most Likely Adoption Rates	South Rift Region	95.61	18.77	114.38	114.22	714.02	98
	Maximum Adoption Rates	South Rift Region	98.64	21.67	120.31	120.15	751.02	90
	Minimum Adoption Rates	**Total**	**44.34**	**23.55**	**67.89**	**67.48**	**165.13**	**88**
	Most Likely Adoption Rates	**Total**	**89.97**	**46.71**	**136.67**	**136.26**	**332.43**	**86**
	Maximum Adoption Rates	**Total**	**105.63**	**53.92**	**159.55**	**159.14**	**388.07**	**82**
Weekly Fungicide Application	Minimum Adoption Rates	Eastern and Central Region						
	Most Likely Adoption Rates	Eastern and Central Region						
	Maximum Adoption Rates	Eastern and Central Region						
	Minimum Adoption Rates	North Rift Region	(0.44)	0.81	0.37	0.35	28.49	67
	Most Likely Adoption Rates	North Rift Region	(0.01)	1.62	1.61	1.59	124.78	74
	Maximum Adoption Rates	North Rift Region	0.66	1.84	2.50	2.48	193.87	82
	Minimum Adoption Rates	South Rift Region	3.56	0.77	4.33	4.32	369.61	104
	Most Likely Adoption Rates	South Rift Region	6.35	1.55	7.90	7.89	673.72	97
	Maximum Adoption Rates	South Rift Region	6.54	1.75	8.30	8.29	707.97	89
	Minimum Adoption Rates	**Total**	**3.12**	**1.58**	**4.70**	**4.67**	**191.06**	**91**
	Most Likely Adoption Rates	**Total**	**6.33**	**3.17**	**9.50**	**9.48**	**386.39**	**88**
	Maximum Adoption Rates	**Total**	**7.20**	**3.59**	**10.79**	**10.77**	**438.87**	**86**

∆ *B-∆ C means the change in benefits minus the change in costs and is otherwise known as the net benefits. ∆ B/∆ C means the change in benefits divided by the change in costs.*

Appendix 9. Potential economic benefits of 3R-gene potato varieties to farmers and consumers in scenario with yield loss abated halved (present value of R&D benefits in millions 2020 USD).

			Δ Farmer Surplus	**Δ Consumer Surplus**	**Δ Total Surplus**	**Δ B-Δ C**	**Δ B/Δ C**	**IRR (%)**
No spraying Fungicide Application	Baseline	Eastern and Central Region	4.42	2.84	7.26	7.23	188.21	83
	Yield loss abated halved	Eastern and Central Region	2.19	1.41	3.60	3.56	93.33	70
	Baseline	North Rift Region	3.22	2.55	5.77	5.73	168.04	78
	Yield loss abated halved	North Rift Region	1.60	1.26	2.86	2.83	83.40	66
	Baseline	South Rift Region	7.33	2.00	9.34	9.29	217.20	76
	Yield loss abated halved	South Rift Region	3.60	0.99	4.59	4.55	106.86	65
	Baseline	**Total**	**14.97**	**7.39**	**22.37**	**22.25**	**192.99**	**79**
	Yield loss abated halved	**Total**	**7.39**	**3.66**	**11.06**	**10.94**	**95.41**	**67**
Tri-Weekly Fungicide Application	Baseline	Eastern and Central Region	6.86	12.16	19.03	18.85	109.54	74
	Yield loss abated halved	Eastern and Central Region	3.75	8.62	12.37	12.19	71.21	66
	Baseline	North Rift Region	1.62	2.97	4.59	4.54	97.14	69
	Yield loss abated halved	North Rift Region	1.06	2.10	3.16	3.12	67.01	63
	Baseline	South Rift Region	43.26	11.43	54.69	54.51	311.04	83
	Yield loss abated halved	South Rift Region	31.58	8.09	39.67	39.50	225.64	77
	Baseline	**Total**	**51.74**	**26.57**	**78.30**	**77.90**	**197.37**	**78**
	Yield loss abated halved	**Total**	**36.39**	**18.82**	**55.21**	**54.81**	**139.15**	**72**
Bi-Weekly Fungicide Application	Baseline	Eastern and Central Region	(2.38)	19.30	16.92	16.75	97.41	73
	Yield loss abated halved	Eastern and Central Region	(0.36)	13.33	12.97	12.80	74.70	68
	Baseline	North Rift Region	(3.27)	8.63	5.37	5.29	69.50	64
	Yield loss abated halved	North Rift Region	(1.02)	5.96	4.94	4.87	64.01	63
	Baseline	South Rift Region	95.61	18.77	114.38	114.22	714.02	98
	Yield loss abated halved	South Rift Region	63.22	12.96	76.18	76.02	475.55	90
	Baseline	**Total**	**89.97**	**46.71**	**136.67**	**136.26**	**332.43**	**86**
	Yield loss abated halved	**Total**	**61.84**	**32.26**	**94.10**	**93.69**	**228.88**	**80**
Weekly Fungicide Application	Baseline	Eastern and Central Region	-	-	-	-	--.--	--.--
	Yield loss abated halved	Eastern and Central Region	-	-	-	-	-	-
	Baseline	North Rift Region	(0.01)	1.62	1.61	1.59	124.78	74
	Yield loss abated halved	North Rift Region	(0.01)	1.62	1.61	1.59	124.78	74
	Baseline	South Rift Region	6.35	1.55	7.90	7.89	673.72	97
	Yield loss abated halved	South Rift Region	6.35	1.55	7.90	7.89	673.72	97
	Baseline	**Total**	**6.33**	**3.17**	**9.50**	**9.48**	**386.39**	**88**
	Yield loss abated halved	**Total**	**6.33**	**3.17**	**9.50**	**9.48**	**386.39**	**88**

Δ B-Δ C means the change in benefits minus the change in costs and is otherwise known as the net benefits. Δ B/Δ C means the change in benefits divided by the change in costs.

Appendix 10. Potential economic benefits of 3R-gene potato varieties to farmers and consumers in scenario with doubled R&D costs (present value of R&D benefits in millions 2020 USD).

			Δ Farmer Surplus	**Δ Consumer Surplus**	**Δ Total Surplus**	**Δ B-Δ C**	**Δ B/Δ C**	**IRR (%)**
No spraying Fungicide Application	Baseline	Eastern and Central Region	4.42	2.84	7.26	7.23	188.21	83
	R&D costs Doubled	Eastern and Central Region	4.42	2.84	7.26	7.19	94.10	71
	Baseline	North Rift Region	3.22	2.55	5.77	5.73	168.04	78

	R&D costs Doubled	North Rift Region	3.22	2.55	5.77	5.70	84.02	66
	Baseline	South Rift Region	7.33	2.00	9.34	9.29	217.20	76
	R&D costs Doubled	South Rift Region	7.33	2.00	9.34	9.25	108.60	65
	Baseline	**Total**	**14.97**	**7.39**	**22.37**	**22.25**	**192.99**	**79**
	R&D costs Doubled	**Total**	**14.97**	**7.39**	**22.37**	**22.14**	**96.49**	**67**
Tri-Weekly Fungicide Application	Baseline	Eastern and Central Region	6.86	12.16	19.03	18.85	109.54	74
	R&D costs Doubled	Eastern and Central Region	6.86	12.16	19.03	18.68	54.77	71
	Baseline	North Rift Region	1.62	2.97	4.59	4.54	97.14	69
	R&D costs Doubled	North Rift Region	1.62	2.97	4.59	4.49	48.57	58
	Baseline	South Rift Region	43.26	11.43	54.69	54.51	311.04	83
	R&D costs Doubled	South Rift Region	43.26	11.43	54.69	54.34	155.52	71
	Baseline	**Total**	**51.74**	**26.57**	**78.30**	**77.90**	**197.37**	**78**
	R&D costs Doubled	**Total**	**51.74**	**26.57**	**78.30**	**77.51**	**98.68**	**66**
Bi-Weekly Fungicide Application	Baseline	Eastern and Central Region	(2.38)	19.30	16.92	16.75	97.41	73
	R&D costs Doubled	Eastern and Central Region	-2.38	19.30	16.92	16.57	48.71	61
	Baseline	North Rift Region	(3.27)	8.63	5.37	5.29	69.50	64
	R&D costs Doubled	North Rift Region	-3.27	8.63	5.37	5.21	34.75	53
	Baseline	South Rift Region	95.61	18.77	114.38	114.22	714.02	98
	R&D costs Doubled	South Rift Region	95.61	18.77	114.38	114.06	357.01	85
	Baseline	**Total**	**89.97**	**46.71**	**136.67**	**136.26**	**332.43**	**86**
	R&D costs Doubled	**Total**	**89.97**	**46.71**	**136.67**	**135.85**	**166.21**	**74**
Weekly Fungicide Application	Baseline	Eastern and Central Region	-	-	-	-	--.--	--.--
	R&D costs Doubled	Eastern and Central Region	0.00	0.00	0.00	0.00	-	--.--
	Baseline	North Rift Region	(0.01)	1.62	1.61	1.59	124.78	74
	R&D costs Doubled	North Rift Region	-0.01	1.62	1.61	1.58	62.39	62
	Baseline	South Rift Region	6.35	1.55	7.90	7.89	673.72	97
	R&D costs Doubled	South Rift Region	6.35	1.55	7.90	7.87	336.86	84
	Baseline	**Total**	**6.33**	**3.17**	**9.50**	**9.48**	**386.39**	**88**
	R&D costs Doubled	**Total**	**6.33**	**3.17**	**9.50**	**9.45**	**193.20**	**76**

Δ B-Δ C means the change in benefits minus the change in costs and is otherwise known as the net benefits. Δ B/Δ C means the change in benefits divided by the change in costs.

Appendix 11. Potential economic benefits of 3R-gene potato varieties to farmers and consumers in scenario with fungicide spraying on a tri-weekly basis in a cropping season (present value of R&D benefits in millions 2020 USD).

			Δ Farmer Surplus	**Δ Consumer Surplus**	**Δ Total Surplus**	**Δ B-Δ C**	**Δ B/Δ C**	**IRR (%)**
No spraying Fungicide Application	Baseline	Eastern and Central Region	4.42	2.84	7.26	7.23	188.21	83
	Triweekly fungicide application	Eastern and Central Region	4.42	2.84	7.26	7.23	188.21	83
	Baseline	North Rift Region	3.22	2.55	5.77	5.73	168.04	78
	Triweekly fungicide application	North Rift Region	3.22	2.55	5.77	5.73	168.04	78
	Baseline	South Rift Region	7.33	2.00	9.34	9.29	217.20	76

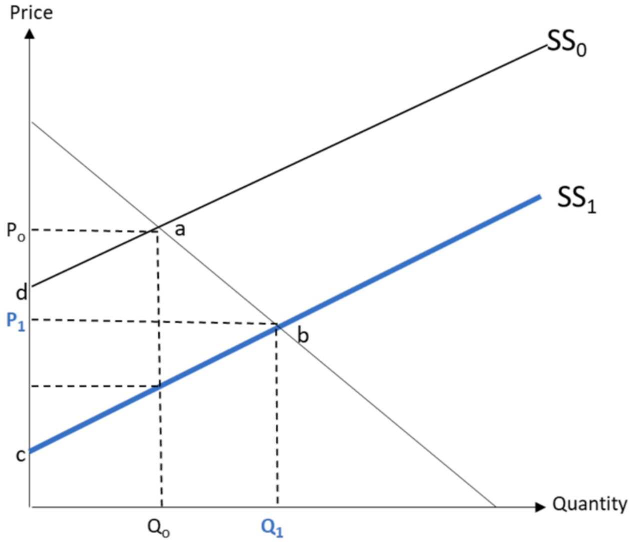
	Triweekly fungicide application	South Rift Region	7.33	2.00	9.34	9.29	217.20	76
	Baseline	**Total**	**14.97**	**7.39**	**22.37**	**22.25**	**192.99**	**79**
	Triweekly fungicide application	**Total**	**14.97**	**7.39**	**22.37**	**22.25**	**192.99**	**79**
Tri-Weekly Fungicide Application	Baseline	Eastern and Central Region	6.86	12.16	19.03	18.85	109.54	74
	Triweekly fungicide application	Eastern and Central Region	6.18	7.72	13.91	13.73	80.06	68
	Baseline	North Rift Region	1.62	2.97	4.59	4.54	97.14	69
	Triweekly fungicide application	North Rift Region	1.26	1.89	3.14	3.10	66.61	62
	Baseline	South Rift Region	43.26	11.43	54.69	54.51	311.04	83
	Triweekly fungicide application	South Rift Region	25.61	7.26	32.86	32.69	186.91	74
	Baseline	**Total**	**51.74**	**26.57**	**78.30**	**77.90**	**197.37**	**78**
	Triweekly fungicide application	**Total**	**33.05**	**16.87**	**49.92**	**49.52**	**125.82**	**71**
Bi-Weekly Fungicide Application	Baseline	Eastern and Central Region	(2.38)	19.30	16.92	16.75	97.41	73
	Triweekly fungicide application	Eastern and Central Region	-4.32	14.90	10.57	10.40	60.87	65
	Baseline	North Rift Region	(3.27)	8.63	5.37	5.29	69.50	64
	Triweekly fungicide application	North Rift Region	-4.83	6.66	1.83	1.75	23.72	49
	Baseline	South Rift Region	95.61	18.77	114.38	114.22	714.02	98
	Triweekly fungicide application	South Rift Region	77.92	14.48	92.40	92.24	576.76	94
	Baseline	**Total**	**89.97**	**46.71**	**136.67**	**136.26**	**332.43**	**86**
	Triweekly fungicide application	**Total**	**68.76**	**36.04**	**104.80**	**104.39**	**254.91**	**81**
Weekly Fungicide Application	Baseline	Eastern and Central Region	-	-	-	-	--.--	--.--
	Triweekly fungicide application	Eastern and Central Region	0.00	0.00	0.00			
	Baseline	North Rift Region	(0.01)	1.62	1.61	1.59	124.78	74
	Triweekly fungicide application	North Rift Region	-0.26	1.01	0.75	0.73	57.95	61
	Baseline	South Rift Region	6.35	1.55	7.90	7.89	673.72	97
	Triweekly fungicide application	South Rift Region	4.17	0.96	5.13	5.12	437.69	89
	Baseline	**Total**	**6.33**	**3.17**	**9.50**	**9.48**	**386.39**	**88**
	Triweekly fungicide application	**Total**	**3.91**	**1.97**	**5.88**	**5.85**	**238.93**	**79**

ΔB-ΔC *means the change in benefits minus the change in costs and is otherwise known as the net benefits.* $\Delta B/\Delta C$ *means the change in benefits divided by the change in costs.*

Appendix 12. Explanation of the DREAM method for calculating the economic benefits of each genetically modified crop and the cost of delay.

The DREAM model (Dynamic Research Evaluation for Management) is a tool to measure the economic impacts of technology adoption in agricultural markets. When a new technology—such as a genetically modified (GM) crop—reduces production costs or increases yield, it shifts the supply curve downward and to the right, as shown in the shift from SS_0 to SS_1 in the figure below. This shift results in a lower market price (from P_0 to P_1) and an increase in quantity (from Q_0 to Q_1).

The following graph from Ruhinduka *et al*. (2020)[33] illustrates measuring welfare effects of a technology through the induced shift of the supply curve:



The welfare effects of this change are captured through changes in consumer surplus (ΔCS) and producer surplus (ΔPS). These surpluses, calculated as follows, together constitute the total surplus (ΔTS), which is represented by the area abcd in the figure above:

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

$$\Delta PS = P_0 Q_0 \left(K - \frac{K\varepsilon}{\varepsilon + \eta}\right)(1 + 0.5\,Z\,\eta)$$

$$\Delta TS = \Delta CS + \Delta PS$$

In these equations:
- $Z = \frac{K\varepsilon}{\varepsilon+\eta}$ represents the proportional reduction in price due to the supply shift.
- K is the vertical shift in the supply curve as a proportion of the initial price P_0.
- ε and η denote the elasticities of supply and demand, respectively.

For more detail, refer to the methods section on pages 40–52 of Wood *et al.* (2001),[35] which describe the DREAM approach, and Alston et al. (1995), which describes the economic surplus method.[57] In order to download the current DREAMpy model, visit https://www.dreampy.org/.

Appendix 13. Explanation of the Carbon Benefits Calculator method for estimating the environmental benefits of each genetically modified crop and the cost of delay.

Below we summarize the relevant aspects of the Carbon Benefits Calculator published in Searchinger *et al.* (2018) that are used in this study.[36] For more detail, refer to the methods section on pages 254–256 of Searchinger *et al.* (2018),[36] which is the publication that first introduced the Carbon Benefits Calculator.

For this study, we used the basic method for estimating the Carbon Opportunity Cost (COC) for crops using the carbon loss method.[36] This involves dividing the carbon lost from vegetation and soils on land used to produce the crop globally by annual production for that crop. Both the figure for carbon lost and the figure for crop production are in kilograms, and the result is multiplied by 3.67 to equal kilograms of CO_2 per kilogram of crop. CO_2e is calculated with the relevant global warming potentials of non-CO_2 greenhouse gases. Discount rates are applied to both the carbon lost and to crop production, which accounts for the fact that conversion of native vegetation to cropland loses carbon quickly compared to the ongoing benefits of crop production on that land. For this study we use the base discount rate, which is 4% over 100 years.[36]

A key assumption of the Carbon Opportunity Cost approach is that if one hectare produces one less ton (or another unit) of a crop, that ton would be produced elsewhere with the global average rate of carbon loss from vegetation and soils caused by producing that crop, and with the global average level of production-related emissions.

Searchinger *et al.* (2018) used vegetation modelling and biome estimates to estimate the native carbon stocks in vegetation and soils of existing cropland.[36]

The carbon benefits (CB; in kg CO2e ha−1 yr−1) are calculated as

CB = COCs + PEMbfits + CARBSTch + FOSsav

Where CARBSTch, and FOSsav were not used for this study because we do not expect soil or vegetation carbon storage on cropland to change or for the use of fossil fuels to change due to adoption of Bt crop varieties; and PEMbfits was not used because though we do expect a change in the pesticide component of production emissions, we do not have sufficient data on the quantity of pesticide application to include it in our analysis; and where

COCs = Y * COC

COCs is the total COC (kg CO2e ha−1 yr−1), Y is a vector of yield(s) of agricultural product(s) (kg product ha−1 yr−1) and COC is a vector of the COC(s) of agricultural product(s) (kg CO2e per kg product).

Appendix 14. Yearly values for output from analysis of economic benefits of Bt maize in Kenya using the DREAMpy model, medium scenario without delay.

Year	Producers					Consumers					Research Costs
	No R&D		With R&D			No R&D		With R&D			
	Price	Quantity	Price	Quantity	Benefits	Price	Quantity	Price	Quantity	Benefits	
	million USD/1000T	1000T	million USD/1000T	1000T	million USD	million USD/1000T	1000T	million USD/1000T	1000T	million USD	million USD
2000	0.19	2424	0.19	2424	0	0.19	2687	0.19	2687	0	0.33
2001	0.19	2477.27	0.19	2477.27	0	0.19	2746.05	0.19	2746.05	0	0.33
2002	0.19	2531.72	0.19	2531.72	0	0.19	2806.41	0.19	2806.41	0	0.32
2003	0.19	2587.36	0.19	2587.36	0	0.19	2868.09	0.19	2868.09	0	0.28
2004	0.19	2644.23	0.19	2644.23	0	0.19	2931.12	0.19	2931.12	0	0.26
2005	0.19	2702.34	0.19	2702.34	0	0.19	2995.54	0.19	2995.54	0	0.23

2006	0.19	2761.73	0.19	2761.73	0	0.19	3061.37	0.19	3061.37	0	0.19
2007	0.19	2822.43	0.19	2822.43	0	0.19	3128.66	0.19	3128.66	0	0.16
2008	0.19	2884.46	0.19	2884.46	0	0.19	3197.42	0.19	3197.42	0	0.13
2009	0.19	2947.85	0.19	2947.85	0	0.19	3267.69	0.19	3267.69	0	0.13
2010	0.19	3012.64	0.19	3012.64	0	0.19	3339.51	0.19	3339.51	0	0.13
2011	0.19	3078.85	0.19	3078.85	0	0.19	3412.9	0.19	3412.9	0	0.13
2012	0.19	3146.52	0.19	3146.52	0	0.19	3487.91	0.19	3487.91	0	0.11
2013	0.19	3215.67	0.19	3215.67	0	0.19	3564.57	0.19	3564.57	0	0.11
2014	0.19	3286.34	0.19	3286.34	0	0.19	3642.91	0.19	3642.91	0	0.1
2015	0.19	3358.57	0.19	3358.57	0	0.19	3722.97	0.19	3722.97	0	0.11
2016	0.19	3432.38	0.19	3432.38	0	0.19	3804.79	0.19	3804.79	0	0.11
2017	0.2	3507.82	0.2	3507.82	0	0.2	3888.41	0.2	3888.41	0	0.1
2018	0.2	3584.91	0.2	3584.91	0	0.2	3973.87	0.2	3973.87	0	0.09
2019	0.2	3663.7	0.2	3666.91	0.94	0.2	4061.21	0.2	4063.95	1.38	0.09
2020	0.2	3744.22	0.2	3758.42	4.2	0.2	4150.46	0.2	4162.63	6.12	0.14
2021	0.2	3826.51	0.19	3871.86	13.52	0.2	4241.68	0.19	4280.56	19.69	0.14
2022	0.2	3910.61	0.19	3992.31	24.55	0.2	4334.91	0.19	4404.95	35.7	0.14
2023	0.2	3996.56	0.19	4095.22	29.79	0.2	4430.18	0.19	4514.77	43.31	0.13
2024	0.2	4084.39	0.19	4188.85	31.66	0.2	4527.54	0.19	4617.1	46.01	0.13
2025	0.2	4174.16	0.19	4280.59	32.35	0.2	4627.05	0.19	4718.3	47.02	0.16
2026	0.2	4265.9	0.19	4374.34	33.06	0.2	4728.74	0.19	4821.71	48.05	0.16
2027	0.2	4359.65	0.19	4470.14	33.79	0.2	4832.67	0.19	4927.39	49.1	0.16
2028	0.2	4455.47	0.19	4568.04	34.53	0.2	4938.88	0.19	5035.39	50.18	0.15
2029	0.2	4553.39	0.19	4668.08	35.28	0.2	5047.42	0.19	5145.75	51.28	0

Appendix 15. Yearly values for output from analysis of economic benefits of Bt maize in Kenya using the DREAMpy model, medium scenario with delay.

Year	**Producers**					**Consumers**					**Research Costs**
	No R&D		**With R&D**			**No R&D**		**With R&D**			
	Price	**Quantity**	**Price**	**Quantity**	**Benefits**	**Price**	**Quantity**	**Price**	**Quantity**	**Benefits**	
	million USD/1000T	**1000T**	**million USD/1000T**	**1000T**	**million USD**	**million USD/1000T**	**1000T**	**million USD/1000T**	**1000T**	**million USD**	**million USD**
2000	0.19	2424	0.19	2424	0	0.19	2687	0.19	2687	0	0.33
2001	0.19	2477.27	0.19	2477.27	0	0.19	2746.05	0.19	2746.05	0	0.33
2002	0.19	2531.72	0.19	2531.72	0	0.19	2806.41	0.19	2806.41	0	0.32
2003	0.19	2587.36	0.19	2587.36	0	0.19	2868.09	0.19	2868.09	0	0.28
2004	0.19	2644.23	0.19	2644.23	0	0.19	2931.12	0.19	2931.12	0	0.26
2005	0.19	2702.34	0.19	2702.34	0	0.19	2995.54	0.19	2995.54	0	0.23
2006	0.19	2761.73	0.19	2761.73	0	0.19	3061.37	0.19	3061.37	0	0.19
2007	0.19	2822.43	0.19	2822.43	0	0.19	3128.66	0.19	3128.66	0	0.16

2008	0.19	2884.46	0.19	2884.46	0	0.19	3197.42	0.19	3197.42	0	0.13
2009	0.19	2947.85	0.19	2947.85	0	0.19	3267.69	0.19	3267.69	0	0.13
2010	0.19	3012.64	0.19	3012.64	0	0.19	3339.51	0.19	3339.51	0	0.13
2011	0.19	3078.85	0.19	3078.85	0	0.19	3412.9	0.19	3412.9	0	0.13
2012	0.19	3146.52	0.19	3146.52	0	0.19	3487.91	0.19	3487.91	0	0.11
2013	0.19	3215.67	0.19	3215.67	0	0.19	3564.57	0.19	3564.57	0	0.11
2014	0.19	3286.34	0.19	3286.34	0	0.19	3642.91	0.19	3642.91	0	0.1
2015	0.19	3358.57	0.19	3358.57	0	0.19	3722.97	0.19	3722.97	0	0.11
2016	0.19	3432.38	0.19	3432.38	0	0.19	3804.79	0.19	3804.79	0	0.11
2017	0.2	3507.82	0.2	3507.82	0	0.2	3888.41	0.2	3888.41	0	0.1
2018	0.2	3584.91	0.2	3584.91	0	0.2	3973.87	0.2	3973.87	0	0.09
2019	0.2	3663.7	0.2	3663.7	0	0.2	4061.21	0.2	4061.21	0	0.09
2020	0.2	3744.22	0.2	3744.22	0	0.2	4150.46	0.2	4150.46	0	0.14
2021	0.2	3826.51	0.2	3826.51	0	0.2	4241.68	0.2	4241.68	0	0.14
2022	0.2	3910.61	0.2	3910.61	0	0.2	4334.91	0.2	4334.91	0	0.14
2023	0.2	3996.56	0.2	3996.56	0	0.2	4430.18	0.2	4430.18	0	0.13
2024	0.2	4084.39	0.2	4087.91	1.05	0.2	4527.54	0.2	4530.56	1.53	0.13
2025	0.2	4174.16	0.2	4189.74	4.69	0.2	4627.05	0.2	4640.41	6.83	0.16
2026	0.2	4265.9	0.2	4315.69	15.08	0.2	4728.74	0.2	4771.43	21.94	0.16
2027	0.2	4359.65	0.19	4449.36	27.37	0.2	4832.67	0.19	4909.57	39.79	0.16
2028	0.2	4455.47	0.19	4563.79	33.21	0.2	4938.88	0.19	5031.75	48.27	0.15
2029	0.2	4553.39	0.19	4668.08	35.28	0.2	5047.42	0.19	5145.75	51.28	0
2030	0.2	4653.46	0.19	4770.32	36.06	0.2	5158.36	0.19	5258.54	52.41	0
2031	0.2	4755.73	0.19	4874.8	36.85	0.2	5271.72	0.19	5373.8	53.56	0
2032	0.2	4860.26	0.19	4981.56	37.66	0.2	5387.59	0.19	5491.59	54.73	0
2033	0.21	4967.07	0.2	5090.67	38.48	0.21	5505.99	0.2	5611.96	55.93	0
2034	0.21	5076.24	0.2	5202.16	39.33	0.21	5627	0.2	5734.96	57.16	0

Appendix 16. Yearly values for output from analysis of economic benefits of Bt cotton in Kenya using the DREAMpy model, medium scenario without delay.

Year	Producers					Consumers					Research Costs
	No R&D		With R&D			No R&D		With R&D			
	Price	Quantity	Price	Quantity	Benefits	Price	Quantity	Price	Quantity	Benefits	
	million USD/1000T	1000T	million USD/1000T	1000T	million USD	million USD/1000T	1000T	million USD/1000T	1000T	million USD	million USD
2001	0.23	22	0.23	22	0	0.23	34	0.23	34	0	0.08
2002	0.24	21.39	0.24	21.39	0	0.24	33.06	0.24	33.06	0	0.08
2003	0.24	20.8	0.24	20.8	0	0.24	32.14	0.24	32.14	0	0.07
2004	0.24	20.22	0.24	20.22	0	0.24	31.25	0.24	31.25	0	0.07
2005	0.25	19.66	0.25	19.66	0	0.25	30.38	0.25	30.38	0	0.06

2006	0.25	19.11	0.25	19.11	0	0.25	29.54	0.25	29.54	0	0.05
2007	0.26	18.58	0.26	18.58	0	0.26	28.72	0.26	28.72	0	0.05
2008	0.26	18.07	0.26	18.07	0	0.26	27.92	0.26	27.92	0	0.04
2009	0.26	17.57	0.26	17.57	0	0.26	27.15	0.26	27.15	0	0.04
2010	0.27	17.08	0.27	17.08	0	0.27	26.39	0.27	26.39	0	0.03
2011	0.27	16.6	0.27	16.6	0	0.27	25.66	0.27	25.66	0	0.03
2012	0.28	16.14	0.28	16.14	0	0.28	24.95	0.28	24.95	0	0.03
2013	0.28	15.7	0.28	15.7	0	0.28	24.26	0.28	24.26	0	0.03
2014	0.29	15.26	0.29	15.26	0	0.29	23.58	0.29	23.58	0	0.02
2015	0.29	14.84	0.29	14.86	0.01	0.29	22.93	0.29	22.93	0.01	0.02
2016	0.29	14.43	0.29	14.47	0.01	0.29	22.29	0.29	22.3	0.03	0.02
2017	0.3	14.03	0.3	14.14	0.03	0.3	21.68	0.3	21.69	0.08	0.02
2018	0.3	13.64	0.3	13.88	0.07	0.3	21.07	0.3	21.11	0.17	0.02
2019	0.31	13.26	0.29	13.67	0.12	0.31	20.49	0.29	20.55	0.3	0.02
2020	0.31	12.89	0.29	13.42	0.16	0.31	19.92	0.29	20	0.39	0.02
2021	0.32	12.53	0.3	13.11	0.18	0.32	19.37	0.3	19.45	0.43	0.02
2022	0.32	12.18	0.3	12.77	0.19	0.32	18.83	0.3	18.92	0.44	0.02
2023	0.33	11.85	0.31	12.42	0.18	0.33	18.31	0.31	18.39	0.44	0.01
2024	0.33	11.52	0.31	12.06	0.18	0.33	17.8	0.31	17.88	0.42	0.01
2025	0.34	11.2	0.32	11.72	0.17	0.34	17.31	0.32	17.38	0.41	0
2026	0.34	10.89	0.32	11.39	0.17	0.34	16.83	0.32	16.9	0.4	0
2027	0.35	10.59	0.33	11.06	0.16	0.35	16.36	0.33	16.43	0.39	0
2028	0.36	10.29	0.33	10.75	0.16	0.36	15.91	0.33	15.97	0.38	0

Appendix 17. Yearly values for output from analysis of economic benefits of Bt maize in Kenya using the DREAMpy model, medium scenario with delay.

Year	Producers					Consumers					Research Costs
	No R&D		With R&D			No R&D		With R&D			
	Price	Quantity	Price	Quantity	Benefits	Price	Quantity	Price	Quantity	Benefits	
	million USD/1000T	1000T	million USD/1000T	1000T	million USD	million USD/1000T	1000T	million USD/1000T	1000T	million USD	million USD
2001	0.23	22	0.23	22	0	0.23	34	0.23	34	0	0.08
2002	0.24	21.39	0.24	21.39	0	0.24	33.06	0.24	33.06	0	0.08
2003	0.24	20.8	0.24	20.8	0	0.24	32.14	0.24	32.14	0	0.07
2004	0.24	20.22	0.24	20.22	0	0.24	31.25	0.24	31.25	0	0.07
2005	0.25	19.66	0.25	19.66	0	0.25	30.38	0.25	30.38	0	0.06
2006	0.25	19.11	0.25	19.11	0	0.25	29.54	0.25	29.54	0	0.05
2007	0.26	18.58	0.26	18.58	0	0.26	28.72	0.26	28.72	0	0.05
2008	0.26	18.07	0.26	18.07	0	0.26	27.92	0.26	27.92	0	0.04
2009	0.26	17.57	0.26	17.57	0	0.26	27.15	0.26	27.15	0	0.04

2010	0.27	17.08	0.27	17.08	0	0.27	26.39	0.27	26.39	0	0.03
2011	0.27	16.6	0.27	16.6	0	0.27	25.66	0.27	25.66	0	0.03
2012	0.28	16.14	0.28	16.14	0	0.28	24.95	0.28	24.95	0	0.03
2013	0.28	15.7	0.28	15.7	0	0.28	24.26	0.28	24.26	0	0.03
2014	0.29	15.26	0.29	15.26	0	0.29	23.58	0.29	23.58	0	0.02
2015	0.29	14.84	0.29	14.84	0	0.29	22.93	0.29	22.93	0	0.02
2016	0.29	14.43	0.29	14.43	0	0.29	22.29	0.29	22.29	0	0.02
2017	0.3	14.03	0.3	14.03	0	0.3	21.68	0.3	21.68	0	0.02
2018	0.3	13.64	0.3	13.64	0	0.3	21.07	0.3	21.07	0	0.02
2019	0.31	13.26	0.31	13.26	0	0.31	20.49	0.31	20.49	0	0.02
2020	0.31	12.89	0.31	12.9	0	0.31	19.92	0.31	19.92	0.01	0.02
2021	0.32	12.53	0.32	12.57	0.01	0.32	19.37	0.32	19.37	0.03	0.02
2022	0.32	12.18	0.32	12.28	0.03	0.32	18.83	0.32	18.84	0.07	0.02
2023	0.33	11.85	0.32	12.04	0.06	0.33	18.31	0.32	18.34	0.15	0.01
2024	0.33	11.52	0.32	11.85	0.11	0.33	17.8	0.32	17.85	0.26	0.01
2025	0.34	11.2	0.32	11.63	0.14	0.34	17.31	0.32	17.37	0.34	0
2026	0.34	10.89	0.32	11.35	0.16	0.34	16.83	0.32	16.89	0.37	0
2027	0.35	10.59	0.33	11.06	0.16	0.35	16.36	0.33	16.43	0.38	0
2028	0.36	10.29	0.33	10.75	0.16	0.36	15.91	0.33	15.97	0.38	0
2029	0.36	10.01	0.34	10.44	0.15	0.36	15.46	0.34	15.53	0.37	0
2030	0.37	9.73	0.34	10.15	0.15	0.37	15.03	0.34	15.1	0.36	0
2031	0.37	9.46	0.35	9.86	0.15	0.37	14.62	0.35	14.68	0.35	0
2032	0.38	9.2	0.35	9.58	0.14	0.38	14.21	0.35	14.27	0.34	0
2033	0.38	8.94	0.36	9.31	0.14	0.38	13.82	0.36	13.87	0.33	0

Appendix 18. Methodology for analysis of benefits of Bt maize in Kenya

Delays to commercialization of Bt maize in Kenya

Development of Bt maize in Kenya began with the Insect Resistant Maize for Africa (IRMA) project in late 1999, followed in 2002 by the first arrival of Bt maize leaf tissue for research use, and the first arrival of Bt maize seed in 2004.[58] Mugo *et al.* (2011) reports results from what they cite as the first Bt maize CFTs in Kenya, which took place in 2005 and 2006.[58] The NBA website entries for regulatory approvals begin in 2011, and the first entry for MON810 is approval for CFTs in 2011, followed by another in 2016. The IRMA project continued from 1999 in three phases, finally ending in 2014. The Water Efficient Maize for Africa (WEMA) project followed, initially focusing mainly on conventional breeding of drought tolerance, and running in two phases from 2008 to 2018; WEMA phase 2 (2013–2018) included breeding for stem borer resistance. Finally, the TELA maize project started in 2018 and is set to conclude in 2028.

For specifically TELA maize varieties with the MON810 Bt trait, the first application was in April 2015 to NBA for limited release for CFTs, which was approved in January 2016. Application to NEMA for approval of the EIA was in April 2016, which was approved in

November 2019. NPTs concluded in March 2021, and by June 2021 KEPHIS recommended 3 varieties from NPTs for commercial release. In October 2022, NBA approved unlimited release and Bt maize was ready for commercialization, but the court cases then paused release to farmers.

The two steps of the regulatory process for MON810 maize that included long delays were approval of the EIA by NEMA, and approval for unlimited release by NBA. We assume that in a more efficient regulatory system, NBA and NEMA would conduct review for limited release and EIA simultaneously, because though they examine different risks, they require similar data submissions. If NBA and NEMA could have reviewed simultaneously and taken 9 months total as NBA did, then the process could have taken 2 years and 10 months less than it did. In addition, NBA didn't approve unlimited release until 1 year and 7 months after NPTs concluded, whereas KEPHIS approved 3 months after NPTs concluded. If we assume that NBA approval for release could have taken 9 months as NBA approval for CFTs did, then there was a 10-month undue delay. We do not assume the 90–150-day timeline would be enough because this does not include pauses when the agency is waiting for additional information from the developer.

Finally, the ongoing court cases blocked commercialization of TELA maize in October 2022, meaning there has been an undue delay of at least 2 years to November 2024. In total, the delays in NEMA approval of EIA, and in NBA approval for unlimited release and commercialization, have delayed release of TELA maize by 6 years so far. Without these delays, the TELA maize varieties submitted to NBA in April 2015 for limited release for CFTs could have reached farmers by at least 2019 rather than 2024 or later, could have reached maximum adoption this year, and could have already delivered substantial benefits.

A previous study of Bt maize in Kenya concludes that if the IRMA project had proceeded as planned, and the country had not instituted a ban on GM crops in 2012, then Bt maize varieties would have reached farmers by 2006.[23] We chose a more conservative date for plausible historical commercialization, considering that the IRMA project first aimed to release Bt maize varieties by the end of Phase II of the project in 2008 but only released conventional varieties, and thereafter shifted its focus to conventional varieties for the remainder of the project in Phase III from 2008–2013.[59] At this point in 2008, work on Bt maize shifted to the WEMA project, which funded preparation of data for regulatory submission to authorise CFTs of the Bt trait,[59] and subsequent CFTs of TELA Bt maize in Kenya from 2013–2014.[60]

Length of simulation

To model the impacts of Bt maize in Kenya, the total simulation ran from the beginning of research and development in Kenya in 2000, to potential commercialization 19 years later in 2019, to maximum adoption 6 years after that in 2025, and for 5 more years to 2030. In the scenario with an additional delay of 5 years, the total simulation was extended to model the same adoption period, totalling 35 years until 2035.

Crop yield increase

TELA maize has both a genetically modified pest-resistant Bt trait and conventionally-bred drought tolerance, but the drought tolerance is similar to DroughtTEGO® maize which is already available. Since Bt is the new trait, and since this report focuses on the cost of delay of GM crops, we examine the additional yield advantage of the Bt trait alone. Considering that the Bt trait mainly serves to decrease pressure of stem boring pests, it mainly increases yield in locations and years when stem boring pests are present, and when they are not otherwise controlled with pesticides. In addition to resistance to stem borers, TELA maize with MON810 Bt is also purported to have partial resistance to fall armyworm, but since no estimates are available of the degree of yield protection, we do not include this in our estimates of yield increases due to the Bt trait.

In Kenya, smallholders produce 70% of all maize on 80% of the country's cultivated area grown with maize.[5] Though good control of stem borers is possible with insecticides, smallholders generally lack access to both this knowledge and to appropriate insecticides. Therefore, on smallholder farms the Bt maize trait is more likely to increase yields, and on larger farms it is more likely to decrease pesticide use.

We estimate the potential yield gains from the Bt trait based on a) how much maize farmers lose due to stem borer pest damage, and b) how much of the loss to stem borers the Bt trait can prevent. To validate our estimates, we compare them to existing estimates of yield gain from field trials and other sources, but do not rely on these existing estimates alone due to various methodological limitations.

Based on field data from Kenya in 2000–2001 one study estimated an average 13.5% yield loss due to stem borer damage across all agro ecological zones.[22] Many studies cite a common estimate of maize grain yield loss in Kenya due to Lepidopteran stem borers of 15% per year.[33,61] One study cites losses in East Africa generally from 34–43%,[62] and a study in Uganda finds an average 23.5% loss.[63] A study in Ethiopia estimates the benefits of TELA maize assuming a 19–24% yield loss to stem borers between zones,[34] and a similar study in Tanzania assumes an average 15% yield loss.[33]

Of the total 13.5% production loss to stem borers in Kenya, 7.2% is due to *B. fusca* and 6.3% due to other stem borers (author's calculations, based on data in Tables 3 and 4 of Groote *et al.* (2011)[22]). Since *C. partellus* and *B. fusca* make up the majority of crop loss from stem borer species across all agro ecological zones in Kenya, and since *C. partellus* and two of the other main stem borers in Kenya are controlled well by MON810 Bt but *B. fusca* is not, we assume that all the 6.3% of crop loss from the remaining non-*B. fusca* stem borers could be reduced by cultivation of TELA maize.

The value of maize crop losses by agro ecological zone shows only the highlands experiencing almost no losses from *C. partellus* (vast majority of losses due to *B. fusca*).[22] Therefore, we assumed that all agro ecological zones besides the highlands will adopt and benefit from Bt maize protection against *C. partellus* and other stem borer species besides *B. fusca*. These zones with potential adoption are responsible for 66% of Kenya's total maize production (the "highland" zone grows 34% of Kenya's total maize production).[22] The maximum average yield increase these farmers could gain by adopting MON810 Bt maize is 10.3%, which we use for the medium scenario.

If total yield loss to stem borers in the country were 10% or 20% instead of 13.5%—and the proportion of loss to *C. partellus* and other stem borers besides *B. fusca* remained constant—then loss to non-*B. fusca* stem borers would be 4.7% and 9.4%, respectively. This would amount to an average potential yield gain in the non-highland regions of 7.5% and 15.7%, which we use for the low and high scenarios, respectively. These values are also close to the 10–15% yield advantage of the Bt trait in TELA maize that we calculated from NPT results below, when comparing all three TELA varieties to the best commercial check.

Data on the yield change due to the Bt trait is available from three main sources. First, Confined Field Trials (CFTs) in Kenya compared Bt varieties with non-Bt isogenic lines, meaning the varieties are genetically identical other than the Bt trait, and all differences in yield can be attributed to the Bt trait. CFTs often include artificial infestation of a pest species and can show the degree of protection from different species of pests. This is particularly important for Bt maize, because the specific Bt trait in TELA maize—MON810, which produces the Cry1Ab toxin—provides differing levels of protection depending on the stem borer species. The main stem borer species in Kenya are *Busseola fusca* Fuller, which predominates in cooler areas of the highlands, and *Chilo partellus* Swinhoe, which predominates in the lowlands, and which together cause the most yield loss; and *Eldana saccharina* Walker, and *Sesamia calamistis* Hampson. The Cry1Ab protein effectively controls three of the four species, excluding *B. fusca.*[61]

Second, National Performance Trials (NPTs) in Kenya took place over one year (2021) for Bt TELA maize in Kenya in 7 testing locations. NPTs compare Bt varieties to commercial checks, which are varieties already grown by farmers. Commercial checks also have other genetic differences from the Bt varieties besides the trait itself, meaning the yield difference is only partially attributable to the Bt trait and is also partially attributable to the drought tolerant genome and to other genetic differences.

Finally, though no Bt maize has been commercialised in Kenya, Bt maize varieties have been commercialised in other countries where data is available on the yield change due to the Bt trait from a wide variety of farms.

KEPHIS data from TELA maize NPTs conducted across 7 different sites in one year shows yield increases of 15%, 17%, and 62% for the three best hybrids awaiting commercial release compared to commercial checks (personal communication, 2024). TELA maize NPTs took place in 2021, and according to experts involved there was little to no drought at the test sites and the trials included artificial infestation with stem borers to ensure uniform pest pressure. The test sites included a range of maize agro ecological zones, including those with *B. fusca* as well as those with most stem borer damage due to *C. partellus* and other species besides *B. fusca*. Therefore, the average yield increases compared to commercial checks seen in NPTs are not mainly due to the drought tolerant genome, and are due to protection from stem borer damage and to any other advantageous genetic differences between the Bt maize and the commercial checks, so the yield advantage due to the Bt trait alone is likely lower than 15–62%.

Since the three best-performing hybrids from TELA maize NPTs are adapted for cultivation in different regions of Kenya, the differences in yield advantage are due to both differences in the improvement over the most commonly grown local varieties (which may be because older varieties with poorer performance are grown in regions with less large farms or farmers that stay up to date with new technology) and in pest pressure and stem borer pest species. Assuming that checks have little to no resistance to stem borer attack, we can compare each Bt variety to the best-performing check overall from any region to get a better idea of how much of the yield advantage may be due to stem borer resistance; this results in yield advantages of 10–15%. However, since stem borer pressure and species vary among regions, some commercial checks may perform worse partly because they are in regions with higher stem borer pest pressure, and not just because they are otherwise lower-yielding.

In contrast, CFTs control for other differences in the genome by using non-Bt isogenic lines, but stem borer pest pressure is much higher than an average year, which overestimates the real-world yield advantage of the Bt trait.

CFTs conducted in Kenya show that under artificial infestation of MON810 Bt maize hybrids with the stem borer *C. partellus*, yields of Bt lines were 40.6% higher than non-Bt isogenic lines when averaged over 3 years.[60]

Several studies find no protection of MON810 against *B. fusca*, compared to effective protection against *C. partellus* and other less prevalent stem borer species in Kenya.[22,58,64] For example, CFTs in Uganda show an average 35.6% increase in grain yield over two seasons in Uganda with Bt and artificial infestation of *C. partellus*, compared to 6% increase in one season with artificial infestation of *B. fusca.*[39] CFTs in Kenya show reductions in MON810 maize leaf damage from *B. fusca* in a greenhouse with artificial infestation, but do not report grain yield changes.[60] In addition, reports from South Africa indicate resistance of *B. fusca* to MON810 Cry1Ab.[65] Therefore, since the yield protection of MON810 against *B. fusca* is very low,[39] and since other sources find no level of protection and cite risk of development of resistance of *B. fusca* to Bt due to low susceptibility, we do not include protection of MON810 against *B. fusca* in any scenario.

Maximum adoption level

We assume in our medium scenario that Bt maize would, at maximum, be adopted by all farmers in agro ecological zones besides the highlands who already grow improved varieties. We estimate that these account for 60% of Kenya's maize production (before losses to stem borers), based on estimates by De Groote *et al.* (2011).[22] Adoption data is only available by percentage of farmers, which is commonly used as a proxy for percentage of production, and production data is in tons.

However, it is possible that not all farmers who grow improved varieties would adopt TELA maize or, on the other hand, that additional farmers would grow it since it provides such large benefits. Two studies assume that adoption of TELA maize in Tanzania and Ethiopia will be higher than existing adoption levels of conventional varieties because it provides protection against both stem borers and drought, two major challenges with limited to no resistance available in conventional maize varieties;[33,34] the study in Tanzania estimates an increase of 20%.[33] De Groote *et al.* (2011) assume that two-thirds of farmers that grow improved varieties will plant Bt maize.[22] Therefore, for the medium scenario we use existing levels of adoption of improved maize varieties (60%), for the low scenario we use two-thirds of the existing figure

(40%), and for the high scenario we use 20% higher than existing adoption of improved varieties (72%).

Years to maximum adoption

According to expert opinion, generally within 4–5 years of commercialization of a GM crop it reaches around 50% commercialization, and in 7–8 years it reaches about 80%. Examples from adoption of GM crops in other countries show a range of timelines like this. India commercialised Bt cotton in 2002, and adoption reached 95% in 2013, after 11 years (ISAAA 2018). Adoption of Bt cotton in Myanmar began in 2006 and reached 75% in 3 years by 2009, and 90% in 10 years by 2016 (ISAAA 2017). In Brazil, where agriculture is more industrialized, both winter and summer Bt maize were commercialised in 2007, and winter maize reached 90% adoption in 5 years by 2012, while summer maize reached 80% adoption after 9 years in 2016 (ISAAA 2016).

Our low, medium, and high estimates of maximum adoption range from 40–72%, which spans the expert estimates of time to adoption percentage of 50–80%. Therefore, we use the middle of the range of years estimated for these adoption rates, which is 6 years.

Cost of pesticides and seed

For the high benefits scenario, we assume the cost of Bt maize seed is equal to that of non-Bt. For the medium scenario, we assume a 20% increase in the cost of seed. For the low benefits scenario, we assume a doubled cost of seed.

For the high benefits scenario, we assume farmers stop spraying all pesticides on maize. For the medium scenario, we assume a 50% reduction in pesticide cost. For the low benefits scenario, we use a small 10% reduction in the cost of pesticides.

Changes in seed and pesticide cost together equate to a 4.5% reduction in the cost of production in the high scenario, a 1.6% reduction in the medium scenario, and a 6.1% increase in the low scenario.

In Kenya, the MON810 Bt trait is under a royalty-free license which could help keep the cost of seeds more similar to non-Bt seed, but does not guarantee low-cost seeds. Two reasons for this are that the improved traits may increase market prices if farmers are willing to pay more, and that seed providers may need to comply with additional requirements for genetically modified seed than for conventional seed and therefore may sell the seeds for a higher price in order to cover the additional costs.[33] Currently in Kenya, the more expensive conventional maize varieties cost about 20% more than other varieties, and some farmers still purchase the more expensive seeds because they are generally higher quality (expert opinion, 2024). For this reason, we include a cost share increase of 20% in our medium scenario.

Though Bt cotton in Kenya is also under a royalty-free licence, prices in 2021 were very high, costing 2,300 KES per kilogram.[8] This high price may have been due to a problem with supply of the Bt cotton seeds from the sole supplier to Kenya, Mahyco, which is based in India.[8] In contrast, non-Bt cotton seed in Kenya comes from multiple different suppliers, many of which are based in Kenya which contributes to more reliable supply and competition that helps keep prices lower. The situation may be different for Bt maize, considering that seed will be produced by multiple companies within Kenya, but there is no legally binding agreement on price with seed suppliers.

Similar patterns have emerged in other countries as well. Bt maize seeds in the Philippines cost on average almost double the price of non-Bt hybrids.[66] In the United States from 1990 to 2013, the price of genetically engineered crop seeds increased by 700% while others increased by only 218%.[67] For this reason, we include a doubled cost share of Bt maize seed in our low scenario.

To calculate the impact of Bt maize on input costs, we assume that seed and pesticide costs are the central value observed across several studies: 6.5% and 4.5% of total production costs, respectively.[50,51,68]

Another study of Bt maize adoption in Tanzania used expert discussions to estimate a maximum decrease in the cost of production due to pesticide use of 2.1%.[33]

Many farmers did not spray their maize crop with pesticides for stem borers before the arrival of fall armyworm, but began spraying after that to reduce damage due to the combined pest pressure (expert opinion, 2024). Therefore, pesticide application may not decrease by much if farmers understand that the Bt maize mainly protects against stem borers rather than fall armyworm; or, alternatively, if farmers think Bt maize protects against all pests, or if protection against fall armyworm is high, then pesticide application could decrease dramatically.

Discount rate

We use a discount rate of 10% in the low, medium, and high scenarios, and we test a discount rate of 5% in the sensitivity analysis. According to data from the Central Bank of Kenya, the Central Bank Rate in Kenya ranged between 5.75–18% from 2008–2024, and besides several peaks and lows has mainly hovered between 7–10%.[46] Therefore, we use 10% as a conservative estimate for the discount rate in our analysis, and use 5% in the sensitivity analysis to reflect the lower end of the range of Central Bank Rates during this time period.

Similar studies of the cost of delay for commercialization of genetically modified crops in Africa use discount rates of 10%, including insect-resistant cowpea and nitrogen-use efficient rice in Ghana,[47] and drought tolerant and insect resistant maize in Ethiopia.[34] Development of Bt cotton in Kenya is a public investment, and public investment projects in many countries use high discount rates around 10%.[47]

Cost of R&D, regulations, and extension

To model the benefits of Bt maize in Kenya, we must include the cost of developing the technology. These costs include adaptive research and development, regulatory review, and extension services to support technology adoption.

Fees associated with regulatory review include KES 850,000 to NBA for approval for environmental release/placing on the market; this approval is valid for 10 years and must be applied for and paid again for a product to remain on the market for longer than 10 years.[69] Costs of regulatory compliance are included in the total funding numbers for the three Bt maize projects in Kenya.

As described in the Regulatory Timeline section above, development of Bt maize in Kenya began with the IRMA project from 1999–2014, continued as part of the WEMA project from 2008–2018, and the TELA maize project will ideally finish shepherding the first TELA varieties through commercialization and adoption from 2018–2028. All three projects were funded by international non-profit organisations, meaning that the proportion of the funding to develop Bt maize in Kenya didn't come from organisations inside the country; however, it is the best indication of the cost of developing Bt maize for Kenya.

Phases I (1999–2003) and II (2004–2008) of the IRMA project focused more on developing Bt maize in Kenya, whereas Phase III (2009–2013) focused more on conventional breeding for insect resistance rather than Bt.[70] Phase I included developing source lines with the Bt genes, training and infrastructure development for biotech work, and identifying conventional stem borer resistance in local germplasm; Phase II included release of conventionally-bred insect resistant maize varieties and continued work towards release of Bt varieties; and Phase III expanded conventionally-bred insect-resistant varieties from Kenya to East and South Africa more broadly.[70]

The WEMA project had a 10-year budget of USD 100 million, including Phase I of the project from 2008–2012 and Phase II from 2013–2018, and took place in Kenya, Mozambique, South Africa, Tanzania, Uganda, and Ethiopia.[59] The main goal of the WEMA project was to develop drought-tolerant maize hybrids for smallholder farmers in sub-Saharan Africa, using both conventional breeding and genetic modification.[59] The WEMA project was not solely focused on drought tolerance, but also funded preparation of data for regulatory submission to authorise CFTs of the Bt trait,[59] and CFTs of TELA Bt maize in Kenya and Uganda.[39,60]

Since the WEMA project was mainly focused on developing drought tolerance traits, and funding was spread over 6 countries, we assume that 20% supported work on the Bt trait specifically and assign USD 3.3 million of the total USD 100 million to development of Bt maize in Kenya. As explained elsewhere in this report, the current TELA maize varieties awaiting commercialization have the MON810 Bt trait in a conventionally-bred drought tolerant background, meaning that of course the WEMA project more broadly contributed to development of TELA varieties rather than the narrow view of the Bt trait specifically; however, we are focusing on the cost of R&D, regulatory compliance, and extension for the Bt trait specifically.

The TELA maize project builds on breeding done under the WEMA project and aims to commercialise maize varieties with either a genetically modified drought-tolerance trait, an insect-resistant trait, or a stack including both. Funding for the TELA maize project from March 2018–June 2024 was USD 27.03 million for 7 countries from 2018–2019, but stopped activities in Tanzania and Uganda in 2020 and spread funds between the remaining 5 countries. Funding for 2024–2028 is estimated at USD 21.5 million for four countries: Ethiopia, Kenya, Mozambique, and Nigeria. This is the last round of funding for the TELA maize project, after which seed companies will be responsible for producing and selling seed for the varieties as for any other variety (email communication with author, Dr. Sylvester Oikeh, 18–22 April 2024). To estimate the proportion of the TELA project funding for Bt maize in Kenya, we assume that half goes to the insect-resistant traits and half to the drought tolerant traits, then divide the total equally between years and countries, which leaves a total of USD 5.65 million for Kenya from 2018–2028.

The authors are not aware of any data on funding for the IRMA project, so we assume the same yearly funding to Kenya as we estimated for the WEMA project, adjusted from 2008 USD (the year WEMA funding began) to 2000 USD (the year IRMA funding began).

Since project years overlap between the end of IRMA and the beginning of WEMA (2008), the end of WEMA and beginning of TELA (2018), and the end of one phase of TELA and the beginning of the next (2024), and since project funding often begins and ends mid-year, we count half of the beginning and ending years as part of the project period (e.g. the first phase of TELA from June 2018 to June 2024 and the second phase from June 2024 to June 2028, meaning the whole project period is 10 years). To cover all years while maintaining total project durations, we assign funding numbers for the overlap years to the earlier project, e.g. 2018 to WEMA and 2024 to the first phase of TELA. All funding numbers are converted to real 2000 USD from nominal USD value for the year of the project for which they were allocated. The total is about 4.8 million in 2000 USD. Yearly values are listed in the table below.

Year of simulation	Year	Yearly funding (million USD, real 2000 value)	Year of simulation	Year	Yearly funding (million USD, real 2000 value)
1	2000	0.33	19	2018	0.09
2	2001	0.33	20	2019	0.09
3	2002	0.32	21	2020	0.14
4	2003	0.28	22	2021	0.14
5	2004	0.26	23	2022	0.14
6	2005	0.23	24	2023	0.13
7	2006	0.19	25	2024	0.13
8	2007	0.16	26	2025	0.16
9	2008	0.13	27	2026	0.16
10	2009	0.13	28	2027	0.16
11	2010	0.13	29	2028	0.15
12	2011	0.13	30	2029	0
13	2012	0.11	31	2030	0
14	2013	0.11	32	2031	0
15	2014	0.10	33	2032	0
16	2015	0.11	34	2033	0
17	2016	0.11	35	2034	0
18	2017	0.10	Total		4.75

Appendix 19. Methodology for analysis of benefits of Bt cotton in Kenya

Delays to commercialization of Bt cotton in Kenya

It took 19 years for Bt cotton to reach farmers in Kenya. We estimate that this timeline could have been shortened by at least 5 years.

There was a significant delay of 5–8 years between when CFTs ended in 2009/2010,[52,71] when Kenya's National Biosafety Authority approved NPTs in 2016,[71,72] and when Kenya's National Environment Management Authority approved NPTs in 2018.[71] Following this logic, we estimate the cost of a 5-year delay in approval for Bt cotton, as we do for Bt maize and late blight disease-resistant potato.

The National Biosafety Committee received an application in 2001 to import and test Bt cotton, with approval from the National Council for Science and Technology in 2003.[52] Kenya's National Biosafety Authority approved Bt cotton for "environmental release and placing on the market" on January 28, 2020. That year in 2020, the Kenyan government distributed 24 tons of Bt cotton seed imported from Mahyco in India.[8] Therefore, we use the total time from the application for importation of Bt cotton seed into Kenya in 2001 until seeds reaching farmers for use outside trials in 2020 as the figure for total time to commercialization of the crop—19 years. We use 19 years for the time to commercialisation in a scenario with delays, and 14 years in a scenario without delays where we subtract a 5-year delay. Therefore, we model the impact of adoption into the future under a scenario with delay from 2001–2033, and a scenario without delay from 2001–2028.

Length of simulation

To model the impacts of Bt cotton in Kenya, the total simulation ran from the beginning of research and development in Kenya in 2001, to potential commercialization 15 years later in 2015, to maximum adoption 8 years after that in 2023, and for 5 more years to 2028. In the scenario with an additional delay of 5 years, the total simulation was extended to model the same adoption period, totalling 35 years until 2033.

Crop yield increase

For our analysis, we used the central values from the triangular distributions for Scenarios 1, 3, and 4 in a previous publication,[25] as we have for other variables; these values for yield increase are 15%, 20%, and 40% for our low, medium, and high scenarios, respectively. Below we validate these yield assumptions we use by comparing to data from CFTs and NPTs.

Since Bt is the new trait, and since this report focuses on the cost of delay of GM crops, we examine the additional yield advantage of the Bt trait alone—rather than the combined yield advantage of the Bt trait and the overall improved genetics of the variety in comparison to the older non-Bt varieties that are widely grown. Considering that the Bt trait mainly serves to decrease pressure of bollworm pests, it only increases yield in locations and years when stem boring pests are present, and when they are not otherwise controlled with pesticides.

Yield increases due to Bt cotton in China, the US, Burkina Faso, South Africa, and India, range from 0–50%.[25] Differences in yield advantage of the Bt trait between these countries are due to many factors, including both extent and quality of pest control, intensity and extent of bollworm infestations, and pesticide resistance. For example, though farmers in India use lots of pesticides to control cotton pests, bollworm and some other pests have developed resistance and therefore application is not very effective; this factor, in addition to high levels of bollworm infestation, contribute to the high-end yield increase from Bt cotton in India, which is around 50%. In contrast, yield increases in China and the US are much lower, often close to 0%.

Though pesticides for control of cotton bollworm and other cotton pests are available in Kenya, and though almost all farmers including smallholders spray some pesticides on their cotton crop, barriers including cost of pesticides and lack of knowledge or training on correct application mean control of cotton bollworm is often suboptimal. Few farmers in Tanzania spray enough pesticides to control bollworm—only 5% of fields are sprayed the recommended 6 times per season, while 10% are not sprayed at all—and this trend extends to most countries in the region.[25]

Since pesticides are widely used in Kenya but farmer knowledge on correct usage is lower, we would expect some level of yield increase on average, rather than just a decrease in pesticide use. In addition, because there is not widespread resistance of bollworms to pesticides in Kenya, we would not expect to see as dramatic a yield increase as has been seen in India. Studies cite the percentage of cotton crop loss due to bollworm in many African countries commonly from 30–60%, often around 50% and sometimes up to 90% or 100%.[8] We would expect the Bt trait to reduce a large percentage of these losses.

In Kenya, NPTs showed a 0–30% yield advantage of the Bt trait compared to non-Bt isolines over two seasons, and CFTs showed a yield advantage of -9–87% without spraying for pests, and 9–25% with spraying for pests. There is considerable variation in yield advantage between seasons of CFTs and NPTs in Kenya, but the yield increase values we use range from the average from CFTs with spraying for pests to the average from CFTs without spraying for pests, rather than the lowest or highest values.[25] Considering that pest control practices are suboptimal on many farms, it would make sense to see higher average yield advantage of the Bt trait than in the CFTs with optimal pesticide application for all pests including bollworms (up to 40% in our high scenario).

The non-Bt isolines are never exactly genetically identical to the Bollgard Bt lines, but comparison to them gives a better sense of the yield advantage of the Bt traits than comparison to commercial checks, which have much different genetics overall. The total advantage of the Bollgard lines compared to the commercial checks is important for the total yield benefit the farmer may see, but it is important to know how much of this yield advantage is due to pest control vs other traits.

Kedisso *et al.* (2023) published basic data from Bt cotton NPTs in Kenya, citing the original report by KALRO which is not publicly available; the following figures were calculated by the author from data in Table 8,[8] which does not specify cultivation conditions or pesticide application. In the first season of NPTs, the four Bollgard lines averaged a yield of 3.125 t/ha, the four non-Bt isolines averaged 3.15 t/ha, and the two commercial checks averaged 2.15 t/ha. The average of the four Bollgard lines was 1% lower than the average of the four non-Bt isolines; and the four individual Bollgard lines had a yield advantage ranging from 2% lower to 21% higher than the average of the four non-Bt isolines.

In the second season of NPTs, all genotypes yielded lower, with the four Bollgard lines averaging 2.45 t/ha, the four non-Bt isolines averaging 2.075 t/ha, and the two commercial checks averaging 1.65 t/ha. In this season, the average of four Bollgard lines was 18% higher than the average of four non-Bt isolines; the four individual Bollgard lines had a yield advantage ranging from 6–30% higher than the average of the four non-Bt isolines. In comparison, the Bt lines had a much larger yield advantage over the average of two commercial checks ranging from 21–78% in season one and 33–64% in season two.

Laibuni *et al.* (2012) published results from three seasons of confined field trials (CFTs) with Bt cotton (Bollgard II 06Z604D) and two non-Bt varieties—one isoline comparator (99M03), and one commercial variety (HART 89M)—under three treatment conditions including no pesticide application, pesticide spraying just for sucking pests, and pesticide spraying for all pests.[52] The isoline comparator is meant to have very similar genetics to the Bt variety apart from the Bt trait itself. All three varieties under all three pesticide treatments had the highest yields in the first season and the lowest in the third season.

Performance varied considerably across seasons, with the Bt variety yielding from 0.5–2.5 t/ha without spraying for pests, and the non-Bt commercial variety yielding from 0.2–1.5 t/ha; this amounts to a 66–127% advantage for the Bt variety over the non-Bt commercial variety. With spraying for all pests, the gap between Bt and non-Bt narrowed—the Bt variety yielded 0.4–2.7 t/ha across seasons, compared to 0.1–2.4 t/ha for the non-Bt commercial variety; this amounts to an 11–224% advantage for the Bt variety.

Compared to the non-Bt isoline, which only has data for seasons two and three, the yield advantage of Bt is smaller, totalling -9% and 87% without spraying for pests in seasons two and three, respectively, and 25% and 9% with spraying for pests. This smaller yield advantage is expected because a new variety, Bt or not, will have improved genetics compared to a widely grown commercial variety that has likely been grown for decades without improvement; the Bt trait adds an additional yield advantage, particularly when pest pressure is high and pesticide application is low or ineffective.

Kenyan farmers interviewed by Science Africa note that they need to spray the Bt variety only about 3 times for non-bollworm pests, compared to 12 times for non-Bt varieties, but that the Bt variety is less drought tolerant and doesn't produce as well in dry years.[73] Some of these farmers said the non-Bt varieties perform better when rain is inadequate. In addition, multiple studies with independent evidence suggest that drought stress contributes to poor performance of Bt cotton.[74]

Maximum adoption level and years to maximum adoption

Given the information below, in our analysis we use maximum adoption rates from scenarios 1, 3, and 4 in a previous publication, which are 20%, 70%, and 90%, respectively.[25] The low scenario reflects a situation in which seed systems fail to reach a majority of farmers with Bt cotton; the medium scenario reflect situations in which the desirability of the trait and improvements in distribution result in a majority of farmers benefiting from the technology; and the high scenario reflects a situation in which the trait is highly effective and desirable, resulting in it reaching almost all cotton farmers in the country

Among eight countries that started growing Bt cotton between 1998 and 2002, adoption in 2009 ranged from 58–86%. Among countries that started later, Burkina Faso started growing Bt cotton in 2008 and reached 29% adoption one year later in 2009, and Brazil started in 2005 and had 14% adoption 4 years later in 2009.[74] In China, though adoption was around 60%, this is estimated as all the areas where Bt-susceptible pests impact cotton crops.[74] Bt cotton adoption in India shows a dramatic increase starting in 2002, with adoption reaching 85% in 2008; and a dramatic increase in Myanmar starting in 2006, with adoption reaching 75% in 2009.[75] In South Africa, within four years of its introduction, the adoption rate of Bt cotton rose from 2.5% to nearly 90%.[25]

Mulwa *et al.* (2013) note that though adoption of Bt cotton in India and South Africa reached 90% within 5 years, these countries prepared farmers for the technology better than COMESA countries are doing;[25] therefore, they assume it's most likely that it will take 9 years for adoption to 70%. Falck-Zepeda *et al.* (2008) also use a 9-year adoption lag for their analysis of the potential benefits of Bt cotton in West African countries.[76] In Kenya, not only Bt technology but even hybrid cotton technology is new to most farmers, and the system must improve considerably to provide farmers with both access to seed and the knowledge to use it correctly.[44]

We use a long adoption lag of 9 years to maximum adoption as in similar analyses,[25,76] because in the four years since commercialization in 2020, distribution of Bt cotton seed in Kenya has faced significant challenges, and because the norm is that current popular varieties often remain widespread for decades before being replaced by improved varieties.

Cost of pesticides and seed

For the high benefits scenario, we assume the cost of Bt cotton seed is 20% higher than non-Bt; for the medium scenario, we assume a larger 50% increase in the cost of seed; and for the low benefits scenario, we assume a doubled cost of seed.

For the high benefits scenario, we assume farmers stop spraying all pesticides on cotton. For the medium scenario, we assume a 50% reduction in pesticide cost and spraying labour. For the low benefits scenario, we use a small 10% reduction in the cost of pesticides and spraying labour, roughly equivalent to all farmers reducing sprays from all pests to just sucking pests.[52]

Together, the changes in pesticide use and seed cost equate to a 10.2% reduction in the cost of production in the high scenario, a 4.6% reduction in the medium scenario, and a 0.4% increase in the low scenario.

Even when the Bt trait effectively controls the destructive cotton bollworm pests, spraying of pesticides may still be necessary to control secondary pest species, including broad-spectrum pesticides that are also used to control bollworm.[74] The economic impact of secondary pests may become more relevant when a Bt trait controls the primary pests, and may offset some of the decrease in cost of production expected when a Bt trait replaces some pesticide application.[76] For this reason, we include in our medium scenario that pesticide use decreases but only by half.

Pesticide application may not decrease by very much if farmers understand that the Bt trait in cotton mainly protects against bollworms but not all secondary pests, and if controlling those secondary pests is very important; alternatively, if farmers think Bt cotton is protected against all pests, then pesticide application could decrease dramatically. In some cases of Bt cotton adoption, for example in South Africa, farmers often decreased pesticide use to zero for the Bt variety compared to non-Bt.[77] For these reasons, we include in our high scenario the possibility that pesticide use decreases to zero.

The price of Bt cotton seed is often a problem. In Ethiopia, Sudan, and Kenya, the importation of Bt hybrid cotton seeds from the company Mahyco in India has been expensive, and the high price of seed has kept the varieties from being adopted widely in these countries.[8] In addition, in the past in South Africa, the price of Bt cotton seed was almost double that of non-Bt cotton seed, while the cost of pesticides decreased by over half.[78] For this reason, we include in our low scenario that the cost of seed doubles.

Currently in Kenya, the more expensive conventional maize varieties cost about 20% more than other varieties, and some farmers still purchase the more expensive seeds because they are generally higher quality (expert opinion, 2024). We do not have similar data for cotton, but for this reason we use a 20% increase in seed cost for our high scenario as the Bt seeds will be more desirable varieties.

The COMESA Seed Harmonization Implementation Plan provides some framework for improving farmer access to quality seeds.[8] Ideally COMESA countries would establish regional production of Bt cotton seeds, in which case the seeds could reach farmers in 1–2 years.[8] Under a scenario with production of Bt cotton seeds in Kenya or another COMESA country, many of the factors that make seeds imported from India expensive—difficulty of currency exchange, high freight costs for transporting the seeds—would be less and likely the seed price could be much lower.

Currently in Kenya, the cost of Bt cotton seed is subsidised by the government.[8] Since regional production of Bt cotton seed is not yet available in Kenya but may be within the period of our analysis (simulation ends in 2028 without delay and 2033 with delay), we assume the increase in Bt seed price compared to non-Bt seeds is 50% in our medium scenario. This 50% increase is higher than we would expect with regional production, but lower than we would expect with continued importation from India including supply difficulties and more expensive freight costs caused by the COVID-19 crisis.

Using data from CFTs, Laibuni *et al.* (2012) estimate a small decrease in the cost of pesticides and spraying labour when farmers transition from spraying for all pests to spraying for just sucking pests (which aren't controlled by the Bt trait).[52] Cost of spraying for all pests was 47,134 KES, while the cost of spraying for just sucking pests was 44,046, which is a 7% decrease in cost.

We use data on the cost of cotton production in Kenya including 1.4% of costs due to seeds/sowing, 5.8% due to pesticides, and 4.7% due to pesticide spraying labour.[25] Though these data are old, we are not aware of any new information published on the percentage of the cost of cotton production in Kenya due to seeds and pesticides.

Discount rate

We use a conservative discount rate of 10% in the low, medium, and high scenarios, and we test a discount rate of 5% in the sensitivity analysis. Similar studies of the cost of delay for commercialization of genetically modified crops in Africa use discount rates of 10%, including insect-resistant cowpea and nitrogen-use efficient rice in Ghana,[47] and drought tolerant and insect resistant maize in Ethiopia.[34] Development of Bt cotton in Kenya is a public investment, and public investment projects in many countries use high discount rates around 10%.[47]

Cost of R&D, regulations, and extension

Two studies cite very different totals for the cost of adaptive R&D plus biosafety regulations. One study cites $2,000,000 distributed over four years for each of 5 COMESA countries, including Kenya.[25] Separately, a study in West Africa uses an estimated 120,000 USD for adaptive R&D and biosafety regulations over 4 years, and 90,000 USD over 3 years for the rest of their focus countries.[76] Considering our research on the cost of R&D and biosafety for development of Bt maize for Kenya yielded an estimate of almost 5 million USD, and that development of Bt cotton took a similar amount of time, we use the higher estimate of 2 million USD in our assumptions. We spread the total funding equally over the relevant years.

Appendix 20. Methodology for analysis of benefits of 3R-gene potato in Kenya

Delays to commercialization of 3R-gene potato in Kenya

The development of the 3R-gene potatoes followed well established process but suffered significant delays.

The proof-of-concept started with the research on the isolation of genes resistant to late blight from wild potato species, which began in 2008 in CIP headquarters in Lima, Peru. CIP transferred three resistance genes from Argentinean and Mexican wild potato species to the Victoria and Desiree varieties, which are local farmers' preferred varieties in East and Central Africa. This was followed by numerous greenhouse tests over a period of four years to identify the most productive and disease-resistant varieties.

In collaboration with the Kenya Agricultural and Livestock Research Organization (KALRO), selected transgenic potatoes were shipped to Kenya in 2012 for further laboratory and greenhouse tests. Then, in collaboration with Uganda's National Research Organization (NARO) in 2015, selected transgenic potatoes were shipped to Uganda for experimental confined field trials. In 2020, the performance of selected transgenic potatoes in multiple locations and over several seasons were completed, along with risk assessment experiments.[30] An application for the national release of the best biotech potato could not be submitted to Ugandan national competent authorities due to the lack of a law authorizing GM crop commercialization.

In parallel with work in Uganda, CIP and KALRO continued the development of the 3R-gene late blight resistant biotech potato with new potato varieties popular in Kenya, Shangi and Tigoni.[31] Multi-location confined field trials (ML-CFTs) of the 3R-gene potatoes have been conducted at three locations approved by Kenya's National Biosafety Authority (NBA): Muguga, Njabini, and Molo. Cultivation of the 3R-gene potatoes from multiple seasons and locations show that these biotech potatoes, unlike conventional varieties, are completely resistant to late blight disease, requiring no fungicide spray. Phenotypic and agronomic performance and risk assessment experiments were completed successfully in 2024 in Kenya where an application for environmental release of one of the best biotech potatoes, the Event Sha.105, will be submitted to national competent authorities in 2024.

Hence, the development of the biotech potato took about 16 years, which is the double of the originally estimated 7–9 years. This delay was essentially due to the change of GM crop policy in Uganda and the need to shift to a new variety for Kenya.[56]

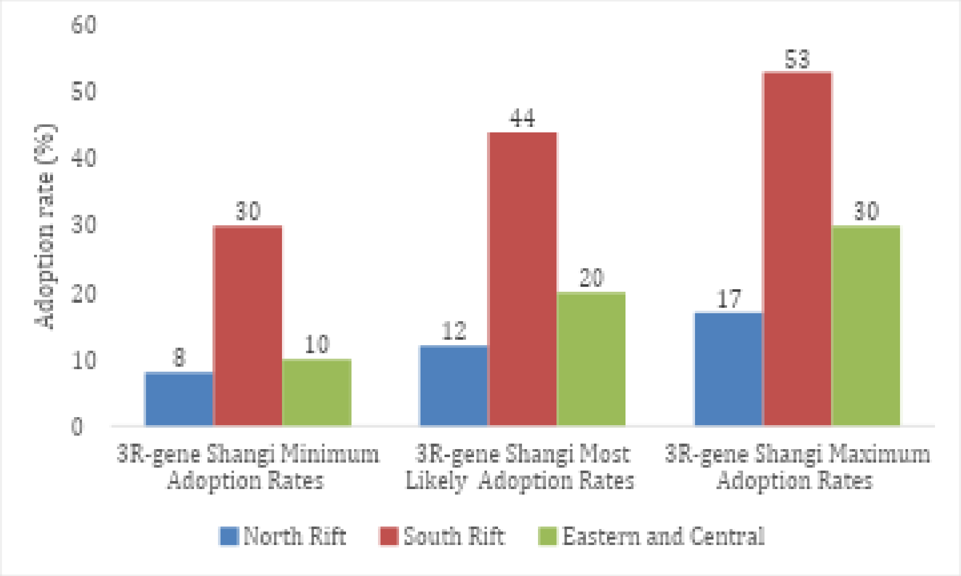
Adoption path

Using the most likely values, experts estimated that, upon regulatory release and commercialization of the 3R-gene Shangi, it would take five to seven years to reach maximum adoption rates, 10 to 15 years at the maximum adoption, and 5 to 9 years for the variety to be abandoned. The most likely values, which are the middle range values, were used in the DREAMpy software to assess the potential benefits.

Adoption levels

We obtained the potential adoption rates of the 3R-gene Shangi from potato experts in the country. Three possible adoption rates of the 3R-gene Shangi were assessed for potential benefits of the technology: minimum, most likely, and maximum adoption rates. The minimum, most likely, and maximum adoption rates range from 8–53% (Figure 12).

Figure 12. Adoption rates of 3R-gene Shangi potato variety

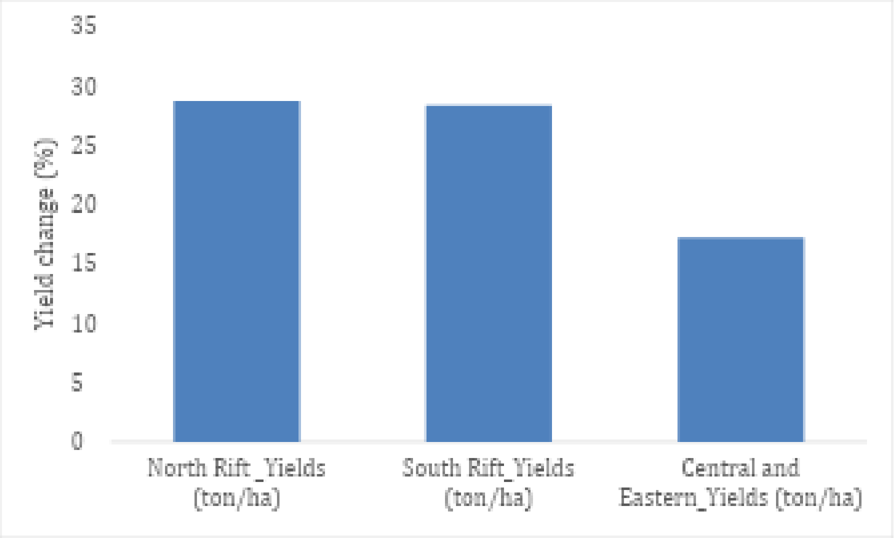


Yield loss abatement

With the adoption of the resistant Shangi potato variety, the anticipated productivity effects are positive owing to the avoidance of yield losses to late blight disease. To obtain the expected yield changes with the adoption of the 3R-gene Shangi variety, key stakeholders along the potato value chain, including farmer representatives and county agricultural extension officers, were asked to estimate a) current yields under different late blight management practices and b) expected yield if the late blight problem was to be solved, holding other factors constant.

On average, the expected yield changes varied from 17.2% to 28.7%, which can be interpreted as the production losses attributed to late blight disease (Figure 13).

Figure 13. Anticipated yield changes with adoption of the 3R-gene Shangi potato variety



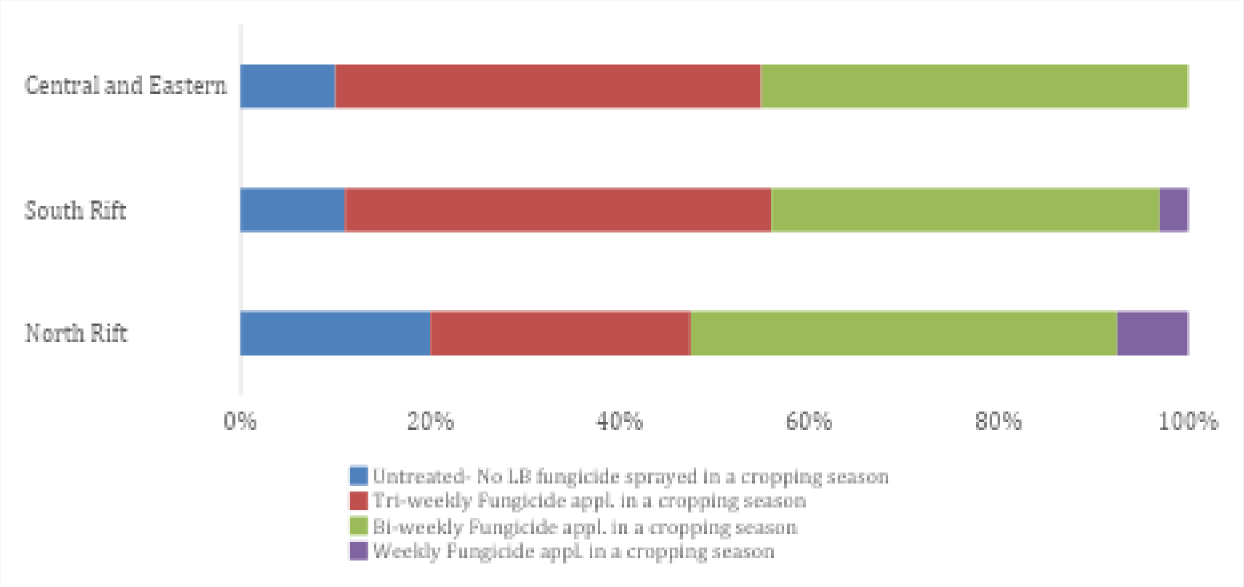
The yield effects were derived as a weighted average of the expected changes across various late blight management practices.

Change in cost of production

In addition to anticipated yield changes, changes in the per-unit production costs are expected given the cost effects of late blight management on production costs, and ultimately on the income earned by farmers.[79,80]

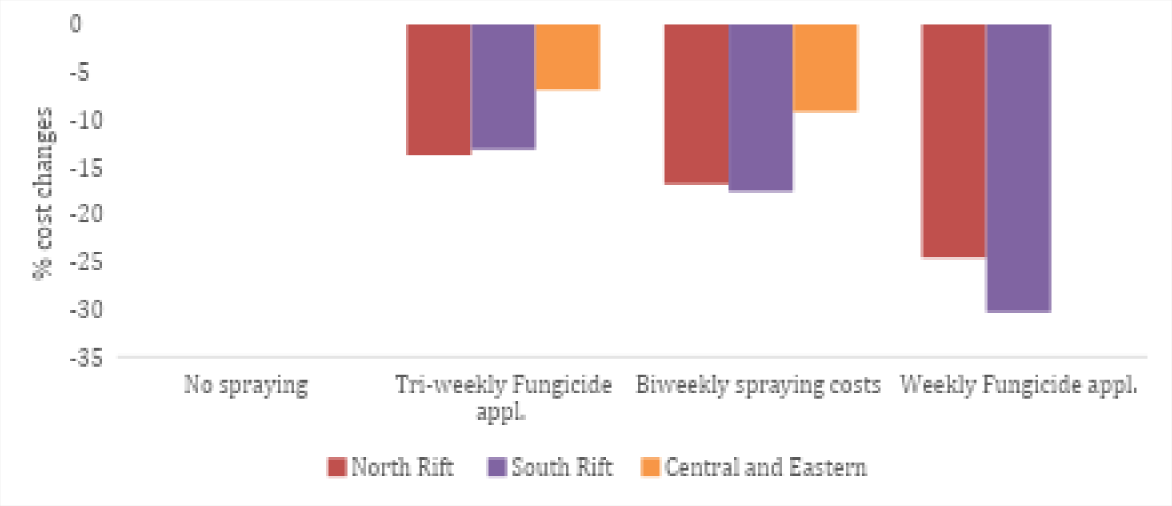
To assess the impact of the 3R-gene Shangi on production costs, a partial production budget for potatoes using conventional varieties was obtained from (Njagi *et al.* 2018).[81] Shangi-specific information was further assessed by potato experts in an expert elicitation workshop. Various fungicide management practices were considered, as per current farmer practices, so as not to overestimate/underestimate the effects of technology on production costs (Figure 14).

Figure 14. Current fungicide application regimes for potato farmers in Kenya by region



The potential per-unit cost reductions assessed ranged from 0% with no spraying to approximately 30% with weekly fungicide applications (Figure 15).

Figure 15. Cost reductions per hectare with 3R-gene Shangi potato variety



<u>R&D costs</u>

The International Potato Center (CIP) incurs the cost of developing late blight-resistant technologies. As with all its developments, the 3R-gene technology will be passed on to the local national agricultural research system (Kenya Agricultural and Livestock Research Organization; KALRO) as the maintainer and seed source. The benefits of this technology are primarily to farmers and consumers. Although neither KALRO nor the government incurs the R&D costs of the technology, consideration of the costs informs the net benefits associated with the development of the technology, which is important in demonstrating the social profitability of the technology,[27] and would inform future work.

Detailed R&D investment costs for late-blight-resistant biotech varieties were obtained.[56] The R&D costs over the various development phases as estimated as: a) Production and selection of pre-commercial events (5 years, 0.78 M); b) Wide-area testing (2 years, US$ 0.33 M); c) Compilation of the regulatory dossier (0.5 years, US$ 0.18 M) ; d) Registration and regulatory affairs (1 year, US$ 0.04 M); and e) Maintenance research costs (2% of total costs; year 9 to 30 years US$ 0.03 M). The total is about 1.3 million in 2020 USD.