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Beyond the Genome: Genetically Modified Crops in Africa and the Implications for Genome Editing

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ABSTRACT

Genome editing — a plant-breeding technology that facilitates the manipulation of genetic traits within living organisms — has captured the imagination of scholars and professionals working on agricultural development in Africa. Echoing the arrival of genetically modified (GM) crops decades ago, genome editing is being heralded as a technology with the potential to revolutionize breeding based on enhanced precision, reduced cost and increased speed. This article makes two interventions. First, it identifies the discursive continuity linking genome editing and the earlier technology of genetic modification. Second, it offers a suite of recommendations regarding how lessons learned from GM crops might be integrated into future breeding programmes focused on genome editing. Ultimately, the authors argue that donors, policy makers and scientists should move beyond the genome towards systems-level thinking by prioritizing the co-development of technologies with farmers; using plant material that is unencumbered by intellectual property restrictions and therefore accessible to resource-poor farmers; and acknowledging that seeds are components of complex and dynamic agroecological production systems. If these lessons are not heeded, genome-editing projects are in danger of repeating mistakes of the past.

INTRODUCTION

In a 2018 essay in *Foreign Affairs* magazine, billionaire philanthropist Bill Gates described his excitement regarding the utility of genome editing — a plant-breeding technology that facilitates the manipulation of genetic traits

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within living organisms — as a tool to alleviate poverty for some of the world's most vulnerable farmers. According to Gates (2018), '[u]sed responsibly, genome editing holds the potential to save millions of lives and empower millions of people to lift themselves out of poverty. It would be a tragedy to pass up the opportunity'. Politicians and policy makers have been equally enthusiastic; for instance, Michael Gove, the former United Kingdom environment secretary, proclaimed that genome-edited crops will be the driving force behind the next agricultural revolution (Brown, 2018). Genome editing was elevated to the global spotlight in 2020 when Emmanuelle Charpentier and Jennifer Doudna were awarded the Nobel Prize in Chemistry for their work on the genome-editing tool CRISPR-Cas9, which the Royal Swedish Academy of Sciences (2020) described as 'bringing the greatest benefit to mankind'.

Genome editing has also captured the imagination of development professionals working on agricultural transformation in Africa, who trumpet it as the next big technological advancement that will 'revolutionize crop improvement' across the continent (Komen et al., 2020: 7; Tripathi et al., 2022). Proponents describe tools like CRISPR-Cas9 as offering 'limitless applications' for improving agriculture in Africa (Mudziwapasi et al., 2018: 200), with the potential to 'usher in a new era of sub-Saharan African prosperity' (Li, 2020: 62). One senior regulatory advisor from the continent claims the technology 'has great promise since it offers a faster, more precise strategy for crop improvement' compared to previous techniques used to create genetically modified crops (cited in Karembu, 2020: 13). In other words, proponents believe that genome editing offers significant opportunities for plant breeders to innovate which, they posit, will translate into improved crops for African farmers.

The optimism that surrounds genome editing echoes earlier narratives underpinning the introduction of genetically modified (GM) crops into Africa. In the early 2000s, Norman Borlaug, often referred to as the father of the Green Revolution, argued that genetic modification was an essential tool to feed a growing global population (Borlaug, 2000). Africa featured prominently within arguments like Borlaug's, which lauded the technology's potential to boost stagnant yields and reduce hunger and poverty among smallholder farmers (Godfray et al., 2010; Juma, 2011). Bill Gates — whose foundation has dedicated well over US$ 170 million towards GM crops and remains one of the largest funders of GM in Africa (GRAIN, 2021) — described GM crops as 'a technique that promises to solve nutrition problems, solve productivity problems, [and] solve crop disease problems for African farmers' (Gates, 2015).

Significant efforts have been made over the past three decades to realize this vision. But the reality of GM crops in Africa has not lived up to the hype: according to data from the International Service for the Acquisition of Agribiotech Applications (ISAAA), Africa accounted for less than 2 per cent of global GM crop planting area in 2019 and only 0.3 per cent if South Africa is excluded (ISAAA, 2019a). Scholars and activists have shown how new seed technologies like GM accelerate the industrial transformation of agriculture and prioritize the interests of capital-intensive farmers,[1] and have questioned the suitability and accessibility of patented seed for Africa's smallholder farmers (Juma, 1989; Kloppenburg, 2004). Social scientists have also unravelled the specific political-economic factors that have hampered the expansion of GM cultivation in Africa. These include the introduction of seeds that demand costly inputs and restrictive crop management regimes (Dowd-Uribe, 2014); limited inclusion of African scientists and farmers in research and breeding programmes (Adenle, 2014); public–private partnerships (PPPs) that prioritize donor over farmer priorities (Muraguri, 2010; Rock and Schurman, 2020); and inadequate evaluation of the compatibility between GM seed technologies and the farming systems they are supposed to enhance (Luna and Dowd-Uribe, 2020).

These critical engagements are conspicuously absent from the current conversation surrounding genome editing. As Bartkowski et al. (2018: 172) have observed, to date there are 'hardly any broad analyses of the potentials and challenges [genome editing] poses … from a social science point of view'. Exceptions include Kuzma (2018), who argues that there are important lessons to be learned from the legacies of GM crops, Shah et al. (2021: 1), who interrogate the 'strategic narrowness' of genome editing narratives, and Montenegro de Wit (2020), who challenges the notion that genome editing is a 'democratizing' technology. In this article, we contribute to these critical insights by combining discursive analysis with empirical evidence to ask: what lessons does the legacy of GM crops in Africa offer in understanding future applications of genome editing? Ultimately, we argue that the continuity in arguments buoying genetic modification and genome editing suggests inadequate reflection on the lessons learned from the past three decades of modern agricultural biotechnology.

This article arose out of a collaboration between seven authors based at institutions in North America, Europe and Africa who, individually and collectively, have been researching the potential for biotechnology to impact agricultural development over the past 30 years. We draw on our perspectives based in different disciplinary as well as institutional backgrounds, bringing together insights from geography, anthropology, development studies and public policy. We have supplemented our own previous research with an extensive literature review on genome editing and agricultural application in Africa, undertaken in 2021.

In the next section, we begin by drawing attention to three major claims — precision, cost and speed — that have been used to describe the potential of both genome editing and genetic modification. These claims deserve scrutiny because their continued use overlooks significant problems

1. See Belay and Mugambe (2021), Canfield (2022), Herren et al. (2019) and Kloppenburg (2004).

that have prevented GM crops from benefiting most African farmers. Following this, we examine what lessons may be learned from the complex legacy of GM crops in Africa by focusing on institutional structures and standards for evaluation. We conclude by offering recommendations for how lessons learned from GM crops might be integrated into future breeding programmes focused on genome editing. To that end, we suggest that donors and policy makers must look beyond the genome, towards systems-level thinking to assess how the much-hyped genome-editing technologies will connect with the social, political and economic contexts of their proposed beneficiaries.

FROM GENETIC MODIFICATION TO GENOME EDITING

Beginning in the late 1980s and early 1990s, advances in molecular mapping allowed scientists to identify genes associated with valuable traits, while techniques of genetic modification enabled breeders to transfer genes from one organism to another, including sexually incompatible organisms (Stone, 2021). Thus, it was possible for genetic engineers to take genes from a common soil bacterium, *Bacillus thuringiensis*, and insert them into plants. Enthusiasts for the new technology crafted narratives around its ability to spark an agricultural revolution by not only improving plants, but also alleviating poverty, assuring food security and promoting economic and human development (Bouis, 2007; Qaim and Kouser, 2013). In the United States, home of many of the early biotech pioneers, GM crops quickly came to dominate agricultural systems; today, over 90 per cent of the corn, soy and cotton crops grown in the US are genetically modified (USDA, 2020). Around the world, GM crops are grown on close to 200 million hectares across 26 different countries (ISAAA, 2019b). However, the vast majority of these GM plantings belong to one of only four major commodity crops: soy, maize, cotton and canola. Of the total area dedicated to GM crops, 88 per cent is covered with herbicide-tolerant crops, including 45 per cent that have 'stacked' transgenic traits comprising both herbicide tolerance and insect resistance (ISAAA, 2019a). Although often cited by GM advocates as an example of the benefits of GM technology, the trait of virus resistance plays a relatively miniscule role in fruit and vegetable production. Other traits with potential value for society, such as drought tolerance or biofortification, are even less well developed.

While the reach of GM crops continued to expand, interest in new techniques of modern biotechnology was evolving too. Genome editing is 'a technique of genetic engineering that involves the alteration of an organism's genetic structure by adding, deleting, changing or replacing individual nucleotides or sequences of DNA. Genome editing includes several different methods and tools, which can be used by breeders to alter the traits of crop plants and livestock animals' (Glover et al., 2020: 2). Genome editing allows scientists to work on targeted nucleotide sequences within a genome, rather than 'randomly [induce] mutations, deletions or genome arrangements' (Pacher and Puchta, 2017: 821), as was the case with genetic modification. It is this delineation that underpins the high hopes many have for genome editing.

Proponents argue that genome editing offers three core advantages for plant breeders, compared to genetic modification: 1) precision: genome editing is supposed to allow scientists to make targeted changes within genomes, with greater precision and control; 2) cost: genome editing is said to have minimal infrastructure requirements and low production costs, making it a widely accessible technology that 'democratizes' molecular plant breeding; and 3) speed: genome editing's purported advancements in greater precision and control should accelerate the pace of crop improvement. On a related note, proponents contend that if genome-edited crops do not contain any foreign genetic material, they should be regulated less stringently than their GM predecessors, which could cut down on the production costs and time it takes to get genome-edited crops from lab to market (Macnaghten and Habets, 2020; Smyth, 2020). These claims are all contested. In what follows, we examine how these narratives of precision, cost and speed are applied to genome-edited crops, and how these echo the enthusiasm that accompanied the release of their genetically modified predecessors.

Claim 1: Precision

When Charpentier and Doudna won the 2020 Nobel Prize for Chemistry for their roles in pioneering a genome-editing tool known as CRISPR-Cas9, the Royal Swedish Academy of Sciences (2020) emphasized the tool's ability to achieve 'extremely high precision'.[2] Plant breeders portray genome editing as a breakthrough technology relative to older techniques of genetic engineering, celebrating it as a 'super precise' tool (Ledford, 2019: 464) that offers 'the widespread ability to control the specific introduction of targeted sequence variation, which provides a game-changing resource for rapid improvement of agricultural crops' (Chen et al., 2019: 670; see also Sukegawa et al., 2021; Xu et al., 2020). Older breeding techniques, including cross breeding, mutation breeding and genetic modification, are now being dismissed by some as 'stochastic' and 'untargeted' (Chen et al., 2019: 669).

This delineation is much messier in practice. Plant breeders often use genome-editing tools like CRISPR-Cas9 as a component within a larger

2. In the decade since Charpentier and Doudna published their influential 2012 article, scientists have continued to develop tools that build off the CRISPR-Cas9 system (Jinek et al., 2012). Newer advancements, such as *SpRY*, an 'engineered … Cas9 variant' that allows scientists to make edits throughout a plant genome, are being promised to provide even more precise forms of in situ genetic manipulation (Ren et al., 2021: 25).

suite of techniques. For instance, Corteva Agriscience[3] recently filed an application for authorization for a glyphosate- and insect- resistant maize (DP915635) with the European Union's Food Safety Authority. The varietal was developed using both CRISPR-Cas9 *and* older genetic modification techniques (Pioneer Hi-Bred International, 2020). Moreover, depending on the type of genome-editing method being used and plant being targeted, the editing process itself might involve the insertion of exogenous DNA, both intentionally, to add new traits not found in the target organism's genome, and unintentionally, as a side effect of the genome-editing process. For example, scientists at the International Institute for Tropical Agriculture used plasmid delivery to genome edit banana and found that the 'selectable marker' used to make edits 'integrate[d] into the plant genome', thus rendering the transformed plant transgenic, because it contained exogenous DNA (Tripathi et al., 2019: 5).

In other words, while CRISPR is often described as transgene-free, and therefore inherently distinct from GM technology, the fact that gene-edited crops may contain small pieces of foreign DNA or whole transgenes makes this narrative misleading (Ho, 2020). The effort to distinguish genome-edited organisms from GM crops, due to the claimed absence of transgenes, is a goal-oriented discursive strategy deployed by stakeholders who find it expedient to highlight technical differences between the two technologies rather than acknowledge their similarities, or overlaps between them (Heinemann et al., 2021).

The attribute of precision was also applied to the technology of genetic modification in its early heyday. Executives at Monsanto worked diligently to build a narrative around GM crops as precise, 'revolutionary, [and] almost miraculous' (Glover, 2010a: 77). Proponents described genetic modification as a significant departure from previous breeding techniques such as hybridization. When it came to transferring genes between organisms, they derided conventional breeding techniques as 'crude practices' (Paarlberg, 2000: 19; see also Dale, 1999; Franks, 1999). Genetic modification was heralded as a technology that was 'cutting edge' and a 'turning point in crop research' because it was more precise, which promised to 'harness [a] genetic revolution' (Serageldin, 1999: 388). One molecular biologist described how, with genetic modification, 'We know where the gene goes and can measure the activity of every single gene around it …. We can show

3. Corteva Agriscience is a transnational agribusiness company that was spun off from the chemical conglomerate DowDuPont in June 2019. DowDuPont was formed from the merger of Dow Chemical and E.I. DuPont de Nemours in 2011 after a subsequent reorganization divided the business into three independent companies. Corteva owns the Pioneer Hi-Bred seed brand, which was acquired by DuPont in 1999. See http://www.corteva.com/who-we-are/our-history.html (accessed 10 June 2021).

exactly which changes occur and which don't' (Goldberg[4] quoted in Freedman, 2013).

In reality, aspects of both genome editing and older techniques of genetic modification are imprecise and haphazard. With earlier techniques of genetic modification, a scientist could excise DNA at precise locations to be assembled into a cassette, but then had no control over where the cassette was inserted into the target organism (which is one important reason why only a tiny percentage of transformed plants were functional). Genome editing with CRISPR is certainly more precise than older techniques in terms of where in the genome it makes cuts, but it can also have a wide range of unintended 'off-target' effects including accidental insertions, deletions and mutations: 'For all the ease with which the wildly popular CRISPR–Cas9 genome-editing tool alters genomes, it's still somewhat clunky and prone to errors and unintended effects' (Ledford, 2019: 464; Heinemann et al., 2021; see also Ely et al., 2021; Mahfouz et al., 2014).

Claim 2: Cost

The second claim surrounding genome editing is that it brings sophisticated molecular plant breeding techniques within the reach of a wide range of users. A 2015 article in *Nature*, for example, described CRISPR as simple and accessible: 'researchers often need to order only the RNA fragment; the other components can be bought off the shelf [for a] total cost [of] as little as $ 30' (Ledford, 2015: 21). The same article quoted molecular biologist James Haber as saying, 'that [cost] effectively democratized the technology so that everyone is using it …. It's a huge revolution' (ibid.). The low cost of genome editing techniques has spurred some to describe them as 'democratic methods' insofar as 'the low cost of production … and the fast production allow not only private companies and multinationals to develop new biotech crops and animals, but also public–private consortia with non-profit ends' (Ricroch, 2019: 46). Proponents contend that, because of their low cost, genome-editing tools will be more accessible for African scientists and institutions, who in turn will develop crops that better respond to the conditions faced by African farmers (Komen et al., 2020; Mudziwapasi et al., 2018).

Early proponents of genetic modification similarly viewed the technology's affordability and accessibility as key to novel applications that would address important traits and crops that matter to smallholder African farmers. Writing in *The Gene Hunters*, the late Professor Calestous Juma (1989: 4–5) argued that 'unlike previous technological revolutions, biotechnology offers the potential to be applied to decentralized production. It is also amenable to popular participation and can therefore be applied to the

4. Robert Goldberg is a plant molecular biologist at the University of California, Los Angeles.

African situation'. Juma believed 'that the capital-related entry barriers [would be] minimal', facilitating broad access among poorer farmers (ibid.).

Any hope of genetic modification serving as a low-barrier, decentralized technology was dashed by the rise of a highly concentrated biotech industry fortified by strict patent enforcement. The landmark 1980 judgment of Diamond versus Chakrabarty in the United States allowed patents to be extended to living organisms, including GM crops. The ruling sparked companies to compete for patenting rights, augmenting the price tag for both discovery and compliance (van Esse et al., 2020). Spiralling costs precipitated industry consolidation: 'during the first half of the 1990s, there were some eight hundred mergers, acquisitions, and other strategic alliances in the agricultural input industry. There were only about a fifth as many a decade earlier' (Schurman, 2003: 7). Waves of corporate consolidation fuelled by strengthening intellectual property regimes continued into the 21st century; today, the four mega pharmaceutical firms Bayer-Monsanto, ChemChina-Syngenta, BASF and Corteva Agriscience control over 65 per cent of the global seed market (Clapp, 2019, 2021; Howard, 2016).

In the late 1990s, these multinational companies became excited about the potential for genetically modified seeds to help alleviate poverty and hunger in Africa, so they transplanted these seeds (and their strict licensing arrangements) to Africa. The first wave of GM seeds was sold to African farmers as bundles along with associated inputs; these resulted in seed prices that were 30–40 per cent higher than conventional seed, the idea being that this price differential would be offset by associated yield increases (Schnurr, 2012). While some early release data on insect-resistant cotton and maize in South Africa suggested that these upfront seed costs would be more than offset by increased yields and savings on insecticide (Keetch et al., 2005; Thirtle et al., 2003), longer-term studies suggested that this initial success was buoyed by subsidies and preferential agreements; once these disappeared, the increased costs associated with GM seed proved prohibitive for farmers (Schnurr, 2012). Fischer et al. (2015) found in 2008 that insect-resistant Bt maize was sold in South Africa at a price five times higher than the variety of certified maize seed that smallholders most commonly purchased, while data from 2019 suggests that GM maize had become 10 times more expensive than certified maize varieties commonly purchased by South African smallholders (Fischer, 2022).

The restrictive patents and high costs that stymied the adoption of this first generation of GM crops precipitated a concerted effort on the part of development donors to create GM versions of African staple crops that would be unencumbered by either (Schnurr, 2015). At the turn of the 21st century, the Rockefeller Foundation partnered with biotech giants to form the African Agricultural Technology Foundation (AATF) to mediate agreements between private seed companies and African scientists, believing that such a partnership would allow for African farmers to access technologies that would otherwise be inaccessible behind patents (Schurman, 2017). AATF and its supporters set out to develop genetically modified versions of African carbohydrate staple crops such as rice, cowpea and maize that could better resist pests, disease and drought. Yet, despite backing from some of the world's largest and most powerful development donors, including and especially the Bill & Melinda Gates Foundation (BMGF), the promise of creating GM crops specifically designed for, and accessible to, African farmers has yet to be realized. Although AATF negotiated royalty-free licences from some of the world's largest agribusiness companies, the PPPs mediated by AATF have been slow moving. As of 2022, only one of these projects — Bt cowpea in Nigeria — has reached the stage of commercialization while several others that remain mired in scientific and regulatory delays include Water Efficient Maize for Africa, nutritionally enhanced cooking banana in Uganda and virus-resistant cassava. These ongoing delays stem from PPPs that prioritized the interests of multinational corporations over those of African scientists and farmers, relied upon unstable funding from international donors, and attempted to operate in countries that lacked permissive legal and regulatory policies regarding biotechnology (Schurman, 2018).

The trajectory of industrial consolidation and the history of previous attempts to transplant existing GM technologies into new African environments should give pause to those heralding genome editing's low cost as the key to ensuring access and affordability for African farmers. Among the Africa-specific crops currently in the genome-editing pipeline, few are housed within African research or higher educational institutes. What's more, as institutions vie for patents around various components of genome editing, questions remain over how patent rules will impact the cost and usage of products, influence research and design, and restrict access to the tools and/or products of genome editing, as they did with genetic modification (Martin-Laffon et al., 2019; Montenegro de Wit, 2020).

Patent filings for genome editing technologies have increased more than 15-fold since 2005 (Brinegar et al., 2017: 925; Graff and Sherkow, 2020). Some of the largest patent holders are research institutions, including the Massachusetts Institute of Technology with 113 patents, Harvard College with 109 patents, the Broad Institute with 86 patents, and the University of California with 73 patents (Martin-Laffon et al., 2019). Graff and Sherkow (2020: 525, emphasis added) note that 'it appears that commercial development of the technology is proceeding at a fast clip *even with little certainty of freedom to operate downstream*' and warn that 'this will not necessarily remain the case in the long run'.

The rapid pace at which academic institutions and their commercial arms have filed for patents '[has] created concern among scientists and legal experts that they might deter or slow down the development and utilization of the technology by establishing proprietary control over what may be considered an essential research tool' (Egelie et al., 2016: 1025). Similar to patent regimes surrounding genetic modification, the patenting of genome-editing technologies circumscribes the space available for future humanitarian and public-good ventures in genome editing. The broad array of CRISPR-related patents held by Corteva Agriscience means that future ventures seeking to apply its proprietary techniques or constructs will need to enter into licensing agreements with the company (Egelie et al., 2016: 1028). This situation is already unfolding within the world's largest research institute, CGIAR;[5] the International Rice Research Institute (Philippines) and the International Maize and Wheat Improvement Centre (Mexico) have both licensed CRISPR technologies from the Broad Institute and Corteva to use in their research programmes (IRRI, 2018; Mollins, 2017).

The patenting trends underway could result in a concentration of corporate control similar to that which constrained the release of GM technology. Whether the patenting of CRISPR technologies and applications will result in 'conflict [or] cooperation' (Sherkow, 2018: 8) remains to be seen. Georges and Ray (2017: 9) argue that the 'genuine resentment of licensing controls imposed by large companies to maximize profits' could be a hindrance to public acceptance of genome-edited crops; they suggest that 'governments should exercise more control … over the establishment of reasonable licensing rules'. In the absence of a more interventionist approach, it seems likely that access to genome-editing technology will be limited by both cost and restrictive patent agreements.

Claim 3: Speed

The third and final claim underpinning genome editing is that it is faster, both in terms of its technical facility and the time it takes to get from lab to market. The first claim regarding the speed of genome editing is best understood within the spectrum of plant-breeding techniques. Conventional plant breeding is generally regarded as 'inherently random and slow, constrained by the availability of desirable traits in closely related plant species' (Barrows et al., 2014: 99). When genetic modification emerged in the late 20th century it was praised for its ability to shorten the process of trait improvement from a 'minimum of 7 to 10 years' with conventional breeding down to five to six years with GM (Sharma et al., 2002: 382). But with the advent of genome editing, GM is now being depicted as slow, clunky and cumbersome: the identification, isolation and characterization of the desired gene is often described as 'time consuming' (Jacobsen et al., 2013: 653), while the introgression of target traits via backcrossing and selection is another 'limiting factor slowing down the breeding process' (Wolter et al., 2019: 1). In contrast, genome editing allows for 'immediate pyramiding of multiple

5. CGIAR (Consultative Group for International Agricultural Research) is a global partnership that unites organizations engaged in research for a food secure future. It is headquartered in France.

beneficial traits into an elite background within one generation' (ibid.), which can halve the amount of time needed to complete the breeding process (Gao, 2021).

Second, proponents argue that the fact that genome-edited crops may lack transgenic DNA should enable them to avoid the more burdensome regulations that slowed down the commercialization of GM crops. There is a widely held opinion among biotech advocates that genetically modified crops have been subject to over-regulation on the African continent, which has stymied commercialization and innovation (Qaim, 2020; Smyth, 2020; Thomson, 2021). Complaints have centred around what some see as prohibitive and overly cautious biosafety legislation, as well as underfunded biosafety bodies and a lack of capacity building in both plant breeding and regulatory oversight (Nang'ayo et al., 2014). Proponents remain hopeful that genome editing will make it possible to avoid these same regulatory hurdles that thwarted their genetically modified predecessors (Lassoued et al., 2019; Waltz, 2019).

How likely is this? In the early days of genetic modification, proponents underestimated the amount of scepticism it would generate. In the early 2000s, few African countries had any sort of biotech regulations or regulating agency in-country. Global development donors, including national governments, the BMGF, Rockefeller Foundation and US Agency for International Development, soon set up dedicated projects such as the Global Environmental Facility, African Biosafety Network of Expertise and Programme for Biosafety Systems to assist countries to establish regulations, set up national biosafety authorities and train regulators. While biosafety authorities are meant to be neutral arbitrators, biosafety laws and institutions became important tools for championing the technology, thus blurring the lines between regulation and promotion.

Donors believed that this flurry of activity, along with funding of GMO projects and dedicated communication blitzes, would allow them to build permissive biotech regimes across Africa (or what Schnurr and Gore, 2015, refer to as 'getting to yes'). But results have not been so straightforward. African governments have exerted sovereignty in developing and operationalizing biosafety regulations, passing laws in Ethiopia and Uganda that seek to restrict, rather than facilitate, biotechnology. Additionally, social movements across the continent including the African Centre for Biodiversity and the Alliance for Food Sovereignty in Africa have questioned not only the utility of GM crops, but also the larger structures of development, liberalization and global inequities within which these technologies are embedded (Rock, 2019).

At the time of writing, few African countries have begun to integrate considerations regarding genome editing into existing or new legislation. Only three countries have crafted regulations that specifically target genome editing. Both Kenya and Nigeria have opted for a more permissive approach that '[allow] for case-by-case reviews and exemptions from biosafety review for products that do not have a novel genetic combination' (Komen et al., 2020: 11), while South Africa announced in October 2021 that gene-edited crops would be subject to the same risk assessment as their genetically modified predecessors.[6] Given that many biotech advocates believe that regulatory regimes have hampered rather than helped the promotion of biotechnology on the African continent (Thomson, 2021), it seems likely that proponents will advocate for regulations that contain clear delineations between plants that contain foreign DNA in the final product and those that do not in order to speed up the approvals process and help genome-edited crops avoid the pitfalls that befell many GM crops. Whether such regulations will be accepted by African politicians and publics is another question altogether.

LEGACIES AND LESSONS

The significant challenges GM crops have faced in Africa offer important lessons for those interested in utilizing genome editing to benefit the continent's farmers. In the remainder of the article, we depart from the three claims presented above to offer alternative, or perhaps additional, considerations to include in future conversations regarding the potential of genome editing in Africa.

Institutional Structures Matter

As donors turn their attention towards supporting new tools in genome editing, significant questions that linger are who will use the tools, how projects will be facilitated and where scientific inquiry will take place. While both genetic modification and genome editing techniques are sometimes made freely available for research purposes, the reality is that both require significant infrastructure, investment, tools, expertise and time. In this section, we explore how the power dynamics of GM developmental partnerships in Africa have shaped outcomes and draw insights on how genome editing technologies might avoid some of the pitfalls — top-down planning, lack of responsiveness to farmer preferences and concerns, restrictive intellectual property — that befell their genetically modified predecessors.

GM crops have been developed and/or commercialized on the African continent through three basic modes. The first is the most straightforward: the sale of GM seeds by a private company in a commercial market, exemplified by the cases of insect-resistant cotton and maize in South Africa, detailed above. The second is a situation where a private company partners with a state research council to co-develop and sell seeds. For instance, in an example we explicate below, Burkina Faso partnered with Monsanto to

6. For critiques of the South African approach see ISAAA (2022) and Lloyd et al. (2022).

insert the company's patented Bt technology into local cotton cultivars. The third way GM crops are commercialized is the most complex: through PPPs between private companies, state research councils and an intermediary organization, the AATF. We are mainly concerned with the latter two types of partnerships, for it is these which Bill Gates and other proponents most often look to as not only being able to 'solve nutrition problems, solve productivity problems, [and] solve crop disease problems for African farmers', but also as 'technological exchanges' for the professional scientists and plant breeders involved (Gates, 2015).

The reality of such partnerships is not so straightforward. In a study of Ghanaian and Nigerian scientists and policy makers involved in biotech development, Adenle (2014: 259) found that 'most respondents complained about little or no involvement of local scientists in developing new improved crop varieties'. This may be due to the multi-layered, multi-actor projects many African scientists find themselves in. Projects overseen by the AATF involve numerous research councils, funders, private actors and others in a 'complex choreography' of interests and conditions that must be satisfied for a crop to move through research and development (R&D) and to commercialization (Rock and Schurman, 2020).

In Uganda, a BMGF-funded project that aims to enhance pro-Vitamin A content in the matooke banana through biofortification featured little input from Ugandan farmers. While farmers across Uganda's banana-growing regions were eager for GM to be used to address pest and disease, nutrition improvement ranked low on farmers' listed priorities for banana enhancement (Schnurr et al., 2020). But biofortification was very much in vogue amongst donors, hence the decision to prioritize this trait amongst others.

In some cases, the distribution of GM crops has been dominated by a top-down model. For example, in Burkina Faso and South Africa, GM seeds have been bundled with larger input packages supplied by companies or governments (Fischer et al., 2015; Luna and Dowd-Uribe, 2020). Input packages provide diverse incentives for farmers, who may opt in to access the seeds, or perhaps another aspect of the package, such as credit or ploughing services. Centralized distribution of input packages can also produce challenges for farmers. In the early 2000s, Burkina Faso partnered with Monsanto to introgress Monsanto's insect resistant Bt genetic technology into a local cotton cultivar. When the state decided to adopt Monsanto's Bt cotton in 2008, a vertically organized industry allowed for massive distribution; by 2013, approximately 70 per cent of all cotton grown was genetically modified (Dowd-Uribe and Schnurr, 2016: 164). However, when issues arose with the Bt cotton — it produced an inferior fibre compared to the previously used conventional variety — top-down distribution chains also meant that the decision whether to continue growing Bt cotton landed with the cotton companies. And indeed, regardless of whether Burkinabè farmers desired to continue growing Bt cotton, ultimately the cotton companies made an executive decision to revert to growing conventional cotton varieties (Luna and Dowd-Uribe, 2020).

The examples above suggest that much of the effort to bring GM crops to the continent has largely been a top-down model driven by donors, with little space for African farmers, breeders, agronomists and civil society to influence agendas. This is not to diminish the important role African scientists and officials have played in shaping biotechnology and biosafety programmes on the continent, nor the roles they are playing now to shape the future of genome editing. Instead, we shine a light on how the power dynamics of GM developmental partnerships have shaped outcomes to underscore important insights on how future plant breeding technologies might avoid some of the drawbacks of their genetically modified predecessors. Breeding projects that are comprised of overly complex partnerships and/or are not embedded within farmer needs, grounded expertise and understanding of local contexts run the risk of failing, regardless of the type of technology used.

Lack of Systematic Evaluation

Much has been made of the potential for GM crops to increase food production for the world's poorest farmers. Initial reports for early adopters in India, South Africa and Burkina Faso showed great promise. However, in the decades since early adopters first planted GM crops, a clearer, yet more complicated, picture has begun to emerge. Recent studies have exposed how different types of evaluation methods — including ex-ante studies, econometric models and studies based on experimental trials rather than farm-level data — have tended to exaggerate benefits and obscure realities associated with GM crops (Schnurr and Dowd-Uribe, 2021). Another methodological issue that has arisen concerns conflicts of interest on the part of those undertaking the evaluation. Indeed, across the African continent, scholars have raised the issue of a 'high proportion of assessment studies undertaken by individuals or institutions that are also responsible for the dissemination of these biotechnologies' (Schnurr, 2019: 198).

The example of Burkina Faso highlights the importance of sound reporting methods, and the troubles that arise without them. The government's announcement in 2016 that it had decided to stop the cultivation of Bt cotton came as a shock to many observers. However, subsequent research and analysis revealed that: 1) Monsanto and Burkinabè scientists had known and been concerned about poor lint quality since 2006; 2) yield gains were substantially less than reported; and 3) farmers reported diverse outcomes with Bt cotton, with wealthier farmers usually benefiting more from Bt cotton cultivation than poorer framers (Luna and Dowd-Uribe, 2020: 2).

After nearly a decade of use, how could so many complications go under-reported? One reason is that Monsanto funded the research process, including evaluations, which may have biased researchers against publicly disclosing issues arising with Bt cotton lint quality. Many evaluations relied on the use of averages, thus 'obscur[ing] substantial variability and differences in outcomes for farmers' (ibid.: 4). What's more, some reporting provided no 'information on the counterfactual (that is, data on conventional cotton yields)', raising questions on how Bt cotton 'yield gains' were calculated (ibid.: 5). Finally, in some cases, the farmers whose crops were used to calculate yield gain were 'model farmers' in that they were wealthier, had larger land holdings and had better access to expert advice than did the average cotton farmer. Glover (2010b: 490) found similar types of persistent biases informed reporting on Bt cotton in India, where one influential study gathered data from farms that 'benefit[ed from] irrigation and "good growing conditions"' despite the fact that a majority of 'cotton in India is grown in rainfed conditions' (Bennett et al., 2004: 96 cited in Glover, 2010b). Such 'placement bias' produces results that '[can] not be generalized to farmers who lacked the benefits of … favorable growing conditions' (Glover, 2010b: 490). Despite the unrealistic pictures that on-farm field trials paint, they remain widely used by biotech proponents. For instance, a recent article published in *Nature Food* cited farm trials of Bt cotton in India to argue for biotech adoption on the African continent (Zilberman and Lefer, 2021).

The above works highlight the importance of independent, longitudinal studies. This point was emphasized recently in a synthesis that mobilized data from the first 17 years of Bt cotton cultivation in India and the three prior years to assess the long-term performance of genetically modified cotton (Kranthi and Stone, 2020). That study showed that surges in cotton yields correlated very poorly with the timing of Bt seed adoption and were better attributed to increased fertilizer use and new insecticides. The widespread adoption of Bt cotton resulted in only ephemeral reductions in pesticide use, which reversed quickly as target pests developed resistance to Bt and non-target pest populations exploded. In this crucial test case — India's Bt cotton is by far the most widely planted GM crop in the global South — farmers are now spending more on insecticides than before Bt seeds were introduced. Kranthi and Stone's (ibid.) article is an important reminder of the dynamic nature of farming and of agroecology. Studies and projects that focus solely on yield increases or short-term performance tend to overlook the complexities and dynamism of farming systems that play an important role in shaping technological outcomes. Such findings offer important lessons for measuring the performance of the next generation of biotechnology.

POLICY IMPLICATIONS

In this article, we have synthesized common threads that bind the now decades-long push to commercialize GM crops across sub-Saharan Africa in the context of the more recent enthusiasm undergirding experiments to create genome-edited crops for smallholder African farmers. We have exposed how these twin cycles of techno-optimism are underpinned by similar emphases on precision, cost and speed. We argue that there are important lessons to be gleaned from the precedent of GM crops that can help to inform this new enthusiasm surrounding genome-edited crops. In conclusion, we offer four policy recommendations for how best to move forward and increase the chances that genome edited crops might better reflect the realities faced by smallholder African farmers.

Reconceptualizing Agricultural Partnerships

As donors, scientists and governments continue to look towards genome editing, there are opportunities to avoid the same bottlenecks that hampered efforts to entrench GM crops on the continent. Key to this will be reconceptualizing and redesigning partnerships that incorporate farmer input in meaningful ways from start to finish. The pipeline of genome-edited crop technologies in Africa should be transformed into a model of technology co-development (Hoffmann et al., 2007), where the breeding priorities and programmes are driven by both African scientists and the smallholder farmers who are the intended beneficiaries. One promising example for how to reconfigure such partnerships comes from a recent 'Africa-led North–South plant genome collaboration' that developed the 'first chromosome-scale plant genome assembly locally produced in Africa' (Njaci et al., 2022: 1). The project was initiated and coordinated by African scientists, who sought out international partners as needed and prioritized in-country, long-term training and information sharing to ensure that the priorities of African farmers and scientists remained front and centre (ibid.). Making such collaborations the norm rather than the exception will require a change of behaviour by development donors, who have a long history of constructing and imposing externally funded agricultural initiatives and emphasizing speed over other considerations of participation and accountability.

To counter this trend, donors should aim for longer-term investments that create space and time for inclusion and mutual learning, embrace broader measures of impact than of adoption and yield rates, and consider implementing local content requirements to enhance capacity building along the product development chain. Investments should be at the level of programmes, not projects, investing in infrastructure and capacity building that reinforces domestic capacity in plant breeding for years into the future (Herdt, 2012). Donors need to move away from the dominant mode of top-down, supply-driven technology pipelines, towards bottom-up, demand-driven agricultural programmes (Brooks, 2014). The starting point for such ventures cannot be 'how can genome edited crops help African farmers?'. Rather, the starting point should be more open-ended, for example, 'what do

African farmers need to improve livelihoods?'. Genome edited crops might be deemed the most strategic intervention in certain cases, but the answer cannot come before the question.

Evaluating Outcomes

The second set of recommendations revolve around how breeding technologies such as genome-edited crops are measured and evaluated. Longer-term, qualitative and multidisciplinary assessments are needed to understand how well any new genome-edited crop will sync with the farming system into which it is designed to be introduced. Too much of the enthusiasm underpinning the release of GM crops was premised on research that was flawed, biased or compromised, resulting in a large gap between the rhetoric associated with these technologies and the realities encountered by the farmers who cultivated them (Glover, 2010b; Kranthi and Stone, 2020).

A new approach to evaluation needs to accompany any release of genome-edited crops: one that is undertaken by independent researchers with no affiliation to the project itself, comprising a multidisciplinary team that includes social scientists alongside agronomists and economists, that integrates farm-based research design rather than relying exclusively on econometric modelling or large-scale surveys. These evaluations should be expanded to include the full breadth and depth of the targeted farming systems (Chambers, 2021; Isgren et al., 2020), rather than manicured experimental field trials, alongside longitudinal analysis that captures the numerous growing seasons. Doing so will allow researchers to ask complex qualitative and quantitative questions, going beyond considerations of productivity to better understand whether the technology fits within broader socio-cultural, environmental, economic and political contexts.

This call for improved evaluation is more than a methodological critique: anticipating outcomes for genome-edited crops requires careful attention to the political and economic relationships that underpin knowledge production. Much of the early data that buoyed enthusiasm for GM crops was produced via donor programming that privileged technological optimism and underappreciated differentiation among farmers (in terms of gender, class, land size and other categories of power) that allowed some to benefit from new technologies while excluding others (Luna, 2020; Schnurr and Dowd-Uribe, 2021). As Luna and Dowd-Uribe (2020: 10) remind us, 'evaluation methodologies which invisibilize politics are an epistemological choice'. An evaluation framework that is more transparent about the productive forces that underpin it and centres farming systems to provide a context-specific assessment of a new genome-edited crop's potential to succeed 'in particular places, for different types of farmers, and over time' will provide a 'more robust and potentially more accurate assessment' of whether genome edited crops will flourish or fail among target beneficiaries (Schnurr and Dowd-Uribe, 2021: 384).

A Call for Honest Brokers (and More Honesty among Brokers)

The third recommendation relates to the need for honest brokers — experts who can communicate both the benefits and drawbacks associated with genome-edited crops in a straightforward manner that serves to 'expand and clarify a scope of choice but allowing others to make decisions according to their own values' (Stone, 2017: 585). Based on contributions from Roger Pielke, Stone (2021) argues that scientists and policy officials need to abandon the 'cloak partisanship' and 'stealth advocacy' that characterized the politicized and polarized debates over GM crops in favour of a more open approach that acknowledges that any new agricultural technology can produce both positive and negative outcomes for a range of different stakeholders and over various timescales.

Of course, a broker is only as honest as their social and political context allows. Critical scholarship has exposed the fallacy of technology neutrality (Fischer, 2016) — any assessment of new technology is inevitably embedded in the positionality and values of the assessor and claims of neutrality serve to legitimize existing power imbalances (Delvenne and Parotte, 2019; Greenberg, 2016; Grunwald, 2019). The debate over GM crops in Africa was dominated by a suite of organizations that positioned themselves as honest brokers to help steer the conversation around agricultural biotechnology in Africa, including Cornell's Alliance for Science, the African Biosafety Network of Experts, and the Open Forum of Agricultural Biotechnology. But critical social scientific research has exposed how these organs functioned as the public relations arm for the very interests seeking to expand the technology's reach on the continent (Harsh, 2014; Munro and Schurman, 2022; Rock, 2022; Schnurr, 2013).

Indeed, the very notion that anyone among us is an honest broker who can offer an objective assessment of a new technology's potential that is divorced from our own biases is a discursive ploy designed to convince the rest of us that the speaker exists beyond the political and economic structures that frame this debate. Such considerations become even more complicated — and indeed essential — at the organizational level, where honest brokering is tied to budgets, grant proposals and maintaining good relationships with collaborators.

Zooming out, African biosafety laws and regulatory institutions have been framed instrumentally as tools to champion new biotechnologies. African regulators should abandon efforts towards promotion and prioritize their role as independent arbiters acting on behalf of public interests, responsible for ensuring health and environmental safety and other legitimate societal and developmental objectives (Kingiri and Hall, 2012). African governments should establish arms-length, independent regulatory bodies that are separate from and independent of the individuals and institutions championing a particular technology or its applications. The role of governments and public sector institutions should be to advance national strategic priorities and facilitate the creation and distribution of public goods, especially to benefit poor and marginalized people and communities, not just to enable private actors to profit from excludable, proprietary technologies.

Overall, the burgeoning conversation around genome editing offers an opportunity to examine critically the values and interests of all those proffering assessments of this new technology's potential. This is essential to ensure that the dominant voices are not just those of individuals or institutions poised to procure gains from the technology's adoption or rejection.

Moving beyond the Genome

Our fourth and final policy recommendation concerns the scale of both the experimental programmes and the broader agricultural development paradigm underpinning the promotion of genome-edited crops into Africa. The current enthusiasm for genome-edited crops — like the preceding rush of enthusiasm that accompanied the expansion of GM crops — is premised upon the idea that changes to a plant's genome can spark widespread change in livelihoods, food security and well-being, but only if and when regulatory barriers that, some argue, blocked GM crops are minimized (Mudziwapasi et al., 2018; Smyth, 2020). A shift in policy is needed, which challenges this reductive framing and recognizes instead that plant breeding is one of many tools in the toolbox for enhanced rural development. The precedent of GM crops in Africa shows that investments in genomic-level enhancement on their own are insufficient to effect long-term change (Dowd-Uribe and Schnurr, 2016). Donors and scientists need to shift from this emphasis on genomic-level investment to systems-level investment to address long-standing challenges facing smallholder farmers; these include concomitant investments in credit, extension, market access, storage and irrigation integrated at the level of project design (Brander et al., 2021; Fischer et al., 2015).

This cannot be achieved by prioritizing the bench sciences of biotechnology and plant breeding over the social and applied field sciences involved in understanding the wider systemic problems (including whether and how an improved variety 'fits' within a particular farming system). Doing so will repeat the mistakes that doomed GM crops whose promise in laboratory, greenhouse or confined field trials was unable to translate into farmer fields. For genome-edited crops to succeed, the agencies behind them will need to embrace a farming and livelihoods systems approach to ensure that their investments in beneficial genomic traits are relevant and useful in the real-world situations encountered by farmers.

CONCLUSION

In this article, we have taken seriously calls from Bartkowski et al. (2018), Kuzma (2018) and Montenegro de Wit (2020) for social scientists to engage in budding debates and scholarship regarding genome editing. To this end, we have drawn from our own collective fieldwork as well as critical assessment of the past 30 years of agricultural biotechnology in Africa to assess ongoing discussions over the role genome editing might play in improving African agriculture. We have argued that narratives surrounding genome editing — especially related to precision, cost and speed — mirror those which accompanied the arrival of previous generations of genetic modification. This synchronicity of discourse between older and newer techniques of genetic modification obstructs clear-eyed assessment of the myriad of obstacles that hampered GM crops in Africa.

Avoiding the pitfalls that stymied past efforts at technological change would likely require the de-commodification of technologies so that they are accessible to a whole host of actors, regardless of geographic location, institutional affiliation, or budget lines. Whether or not this is possible remains an open question. Institutions are scrambling to patent CRISPR tools and innovations. While many of these patents are currently held by educational institutions (*Nature*, 2021), this does not necessarily mean they will be more accessible for researchers, product developers or other users, such as farmers. As we have surveyed here, many patent licences are for research only; any possible downstream commercialization is not guaranteed and would require negotiation. Such an arrangement threatens to recycle the historical system of extracting labour and knowledge of the global South for the benefit of the global North.

Thus, a sober review of efforts to develop GM crops specifically for the African continent warrants reflection from both proponents and opponents. The lessons explored here suggest that proponents of new technologies such as genome editing ought to temper big promises. Instead, the excitement around genome editing offers an opportunity to reimagine and redesign programmes to enhance rural development on the African continent. To move beyond the genome, donors, policy makers and scientists alike must prioritize the co-development of technologies with farmers, seek out non-patented material and acknowledge that seeds are a single component of highly complex agroecological and production systems. Otherwise, no matter how well funded or how valiant the effort, genome-editing projects are in grave danger of repeating mistakes of the past.

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