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Viewpoint: The uptake of new crop science: Explaining success, and failure

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A B S T R A C T

Applications of new crop science often spread widely to reach farm fields, but sometimes they do not. The Green Revolution seeds first released in the 1960s and 1970s were taken up widely and quickly, but the transgenic GMO seeds first released in the 1990s, which also performed well, have remained highly restricted. After more than two decades, 84 percent of all GMO crop acres around the world are still in just four Western Hemisphere countries, and 97.2 percent of total acres are still planted to just four crops. The presence or absence of six "success factors" can explain these divergent uptake trajectories. The success factors are 1) a broad social agreement on the urgent need to boost food production, 2) an immediate and obvious benefit for farmers when they plant the new seeds 3) social trust in the institutions producing and delivering the new technology, 4) an absence of new consumer food safety concerns, 5) an absence of organized opposition from environmental advocacy groups, and 6) the absence of a simple means to detect the altered genetics of the new seeds. The Green Revolution seeds enjoyed all six of these success factors, while GMO seeds enjoyed only one of the six. This same approach can be used to predict the future uptake of genome-edited crops, which show three of the six success factors, predicting a rate of uptake slower than for the Green Revolution but wider and faster than for GMOs. A preliminary scan of national regulatory decisions being made toward genome-edited seeds strengthens this prediction.

1. Introduction

When scientists create improved crop plants, the seeds may be taken up quickly and widely by farmers, or they may be barely used at all. History shows it can go either way. The improved wheat and rice varieties that launched the original Green Revolution of the 1960s and 1970s quickly became pervasive in farm fields from Asia to Mexico, but later in the 1990s when transgenic GMO varieties of wheat and rice were developed, they were not even released for sale to farmers, and in most countries to the present day staple food crops are not being planted in GMO form. Here we identify six key factors that drove these divergent outcomes, then we use those factors to predict the future for crops now being developed through more recent genome-editing methods, such as CRISPR. Will CRISPR crops be widely taken up like the Green Revolution varieties, or will they be blocked by highly precautionary regulations, like so many GMOs?

2. Tale of two revolutions in crop genetics

The new crop science of the Green Revolution was quickly put to use on farms large and small, particularly in Asia. Scientists supported by the Rockefeller Foundation had used conventional breeding methods to introduce new "dwarfing" traits into wheat and rice plants. With shorter stems, these plants devoted less growth energy into producing leaves and straw, and more into producing grain, which allowed yields per hectare to double when adequate water and fertilizer were provided. The new seeds were introduced into India in 1965, performed well, and spread quickly, allowing wheat production to nearly double in just five years. When India began planting the new rice varieties in the states of Punjab and Haryana, production nearly doubled between 1971 and 1976 alone (Chopra, 1981).

The strong uptake of the new seeds in India reflected more than just improved growing traits. The Government of India, partly under persistent diplomatic pressures from the Johnson Administration in the United States, set in place new price guarantees for farmers and invested heavily in irrigation infrastructure and fertilizer imports. These policies

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brought lasting controversy. India's strong political focus on the Green Revolution wheat varieties also brought some damaging neglect of other food crops, such as pulses, but the Green Revolution seeds quickly became pervasive.

For parallel reasons the new seeds spread quickly in Southeast Asia and Latin America as well. The share of harvested rice area in South Asia under modern Green Revolution varieties increased from zero to seventy-one percent between 1965 and 2000, and the share of wheat area increased to ninety-five percent. In East and Southeast Asia, modern rice variety coverage by 2000 was more than eighty percent, and for wheat nearly ninety percent, clear evidence that large and small farms were both participating (Hazell, 2009).

In one study of thirty rice-growing villages in Asia between 1966 and 1972, more than ninety percent of both large and small farms adopted the modern rice varieties within a decade after they became available, and smaller farms actually reached this cumulative adoption level more quickly than large farms (Ruttan, 2004). The seeds worked well on small farms because they could be planted and harvested using traditional hand implements, with no need for expensive powered machinery. The early-phase Green Revolution wheat and rice seeds did not spread rapidly in Africa because most farmers there lacked access to irrigation and fertilizer, and because wheat and rice were not so dominant as food staple crops.

When transgenic (GMO) crop varieties were first developed using rDNA methods in the 1990s, the uptake was anything but pervasive. Herbicide-tolerant soybeans and insect-resistant (*Bt*) yellow maize seeds were widely planted by farmers in the United States immediately after they became available in 1995, because these new crops made it much easier and cheaper to protect against weeds and insects, but in the European Union highly precautionary regulations on GMOs kept them out of farm fields. When most governments beyond the western hemisphere decided to follow Europe's highly cautious regulatory example, the global uptake of GMOs—especially GMO staple food crops—was significantly blocked. Where regulations permitted the commercialization of GMO seeds, they were almost always taken up quickly by farmers, but most national systems effectively blocked commercialization.

As of 2019, 84 percent of all GMO crop acres around the world were in just four Western Hemisphere countries: the United States, Brazil, Argentina, and Canada, and 97.2 percent of total acres were planted to just four crops: soybeans, maize, cotton, and canola (ISAAA, 2019). Except for small quantities of GMO white maize in the Republic of South Africa, these were not staple food crops. Soybeans and yellow maize are used primarily for animal feed, biofuel, or cooking oil; cotton is an industrial crop; and canola is typically crushed for oil or meal. To the present day, staple food crops such as rice, wheat, and potato have scarcely been grown anywhere in genetically engineered form.

3. Explaining divergent uptake trajectories

From these radically different uptake trajectories we can identify six factors likely to permit or block success. The first is a broad social agreement on the urgent need to boost food production. Second is an immediate and obvious benefit for farmers when they plant the new seeds. Third is social trust in the institutions producing and delivering the new technology. Fourth is an absence of new consumer food safety concerns. Fifth is an absence of organized opposition from environmental advocacy groups. And the sixth success factor is absence of a simple means to detect the altered genetics of the new seeds.

In the case of the original Green Revolution in the 1960s and 1970s all six of these success factors were in operation, while in the case of the GMO gene revolution, five of the six were missing, creating the highly divergent uptake trajectories. Fig. 1 summarizes these contrasts. We can consider them one factor at a time.

	Green Revolution	Transgenic GMOs
Social agreement on an urgent need to boost food production	Yes	No
Benefits to farmers that are obvious and immediate	Yes	Yes
Social trust in the institutions producing and delivering the new seeds	Yes	No
Absence of new consumer food safety concerns	Yes	No
Absence of opposition from environmental organizations.	Yes	No
Absence of a simple means to detect the altered genetics of the new seeds.	Yes	No

Fig. 1. Success factors for crop science uptake by farmers: two cases.

4. Social agreement on urgent need to boost food production?

The original Green Revolution seed varieties came along at a critical time in the 1960s when Asian countries like India and Bangladesh were poorly fed and experiencing record population growth. Popular books at the time predicted widespread famine, triggering a Malthusian panic. In 1967, William and Paul Paddock, an agronomist and a former Department of State official, wrote a best seller titled Famine 1975! which projected that India would never be able to feed its growing population. The Paddocks even warned it would be a mistake to give food aid to India because that would keep people alive just long enough to have still more children, leading to even more starvation in the future.

Paul R. Ehrlich, an American entomologist who originally specialized in butterflies, made a parallel argument the following year in a best seller titled The Population Bomb. Ehrlich predicted that hundreds of millions would die in the 1970s due to excessive population growth. He began his book with a memorable pronouncement: "The battle to feed all of humanity is over." (Ehrlich, 1968) Ehrlich projected that by 1980 residents in the United States would have a life expectancy of only 42 years. In this desperate context, the sudden availability of more productive Green Revolution seeds was broadly welcomed as a miraculous achievement, a gift from modern science to a hungry world. In 1970 the scientist who led the crop breeding effort, Norman Borlaug, won the Nobel Peace Prize.

Malthusian worries nonetheless continued and were even amplified in the 1970s by a sudden inflation-driven spike in grain prices on the world market. Between 1971 and 74 the international price of wheat and corn suddenly doubled, while soybean prices rose so high that the United States briefly imposed an export ban in 1973. Time magazine branded this a "world food crisis," claiming that hunger and famine were now ravaging "hundreds of millions of the poorest citizens in at least 40 nations." (Time Magazine, 1974).

These food crisis fears did not wane until the 1980s, when high interest rates and a global recession finally knocked down international food prices. FAO's real food price index fell by 60 percent between 1975 and 2000 (FAO, 2009). Governments around the world concluded from these lower prices that the Green Revolution had finally done its job, implying there was a diminished need for new farm technologies. As a result, international assistance for agricultural development dropped sharply. The percent of official development assistance (ODA) going to agriculture fell from 18 percent in 1979 down to just 3.5 percent by 2004. In a single decade between 1990–91 and 1999–2001, external assistance to agriculture in the developing world declined in real terms by 24 percent (Chicago Council, 2009). In this context, when newly developed transgenic crops first arrived on the market in the mid-1990s they were not welcomed as a miraculous gift from science. Political space had opened up for anti-science critics to depict them as a menace. When international food prices spiked again in 2007–09, international agricultural assistance was revived, but by then the critics of GMO crops had successfully stigmatized this new technology.

5. Benefits to farmers that are obvious and immediate?

As a second success factor, the Green Revolution also delivered benefits to farmers that were immediately obvious. Farmers could see in the field the shorter stature of the plants and the bigger heads of grain, and they could readily count the added bags of harvested wheat or rice that each field now produced. These benefits derived not just from the new seeds, but also from the new irrigation, fertilizer, and supportive price policies.

Obvious and immediate farmer benefits were also a feature of the new GMO crops introduced in the 1990s. Fields of herbicide tolerant soybeans became dramatically free of weeds after just one or two sprays of Roundup. Some weeds eventually developed a resistance to this chemical, which forced seed companies to introduce resistance traits for other herbicides, but global GMO soybean acreage has not declined. Fields of *Bt* corn and cotton also showed obvious and immediate benefits. They could be protected against insect damage sometimes with no spraying at all. These advantages explain why farmers have taken up these crops rapidly wherever governments have made them legal to sell and plant. In the United States, three quarters of all soybean acres were planted to GMO varieties just seven years after the seeds were first available (USDA, 2022). In fact, the immediate benefits to farmers were so dramatic that smuggled seeds were often planted by stealth—like soybeans in Brazil, and cotton in India—before governments had given official permission.

6. Social trust in the institutions that produce and deliver the seeds?

On the issue of social trust, Green Revolution seeds and GMO seeds differed dramatically. The Green Revolution seeds were easy to accept because they came not from corporate labs but from not-for-profit philanthropic organizations like the Rockefeller Foundation and publicly funded research institutes like the International Rice Research Institute (IRRI) in the Philippines and the International Maize and Wheat Improvement Center (CIMMYT) in Mexico. They were not patented, and were supplied to farmers by government extension agents, Peace Corps Volunteers, not-for-profit development assistance agencies, and NGOs. In 1966, IRRI distributed its IR-8 rice seeds to Filipino farmers for free.

The transgenic GMO crops that first came on the market in the mid-1990s were not given away by trusted public or non-profit institutions. To the contrary, they came from laboratory scientists working for large profit-making corporations. In addition, a 1980 US Supreme Court decision (Diamond vs. Chakrabarty) had given these corporations a right to patent genetically modified life forms. This blocked farmers in countries with strong patent laws from saving and replanting GMO seeds, reducing access and leading to more mistrust. Monsanto aggressively defended its patents by bringing lawsuits against farmers suspected of infringements. In the case of Monsanto's Roundup Ready soybeans, the same company that sold the patented seeds also sold the patented herbicide that farmers would need to grow the seeds properly. Monsanto, which was still primarily a chemical company at the time, was infamous for having manufactured and sold Agent Orange, an herbicide used to defoliate jungle land, and also destroy crops, in Indochina during America's unpopular Vietnam War.

7. Absence of new food safety concerns?

Another important difference was the absence of food safety concerns in the case of the Green Revolution seeds, in contrast to the strong consumer anxieties that greeted transgenic GMOs. The new Green Revolution seeds did trigger an equity worry in some quarters, that they would only make profits for larger farms, and a concern that they might make India dependent on fertilizer imports, but there were no fears that they might be unsafe to eat. In sharp contrast, fears of consuming transgenic GMO foods became widespread almost from the start, based largely on the novel fact that they contained "foreign DNA." For example, herbicide-tolerant GMO soybeans had been modified with genetic material from an organism with a particularly frightening name: *Agrobacterium* sp. Strain CP4 (Funke,et al., 2006). Genetic materials introduced from unrelated organisms made it easy for critics to depict GMOs as freakish "Frankenfoods."

Government officials tried to explain that the GMO soybeans had been successfully tested for consumer food safety, but trust in these officials had recently collapsed in Europe due to the *BSE* (mad cow disease) crisis plus other regulatory missteps in the mid 1990s. Government officials had originally said meat from animals with *BSE* would be safe to eat, but consumers later learned it could actually prove fatal. European officials finally admitted this mistake in March 1996, precisely the month GMO soybeans began arriving in European ports from the United States. This unfortunate coincidence triggered suspicions about the safety of all GMO foods, fears that were loudly amplified by public media and advocacy groups.

A related concern was environmental: the outcrossing of herbicide resistance traits into wild relative plants, resulting in "superweeds," or an increased resistance of insect pests to *Bt,* creating "superbugs." Weed resistance did eventually develop to glyphosate, although not through an outcrossing pathway. All these concerns had an effect. In Britain and France, the share of the population opposed to GMO foods rose by 20 percentage points between 1996 and 1999 (Lynas, 2018).

8. Absence of opposition from environmental organizations?

Another positive factor at the outset of the original Green Revolution was an absence of opposition from organized environmental groups. Concerned individuals raised environmental questions from the start, but in the 1960s when the new seeds were first distributed to farmers in India, a well-organized global environmental movement did not yet exist. Rachel Carson's influential book, *Silent Spring,* was published in 1962, but it was a treatise against pesticides, not against plant breeders or even fertilizers. In the United States prior to 1970 there was no Environmental Protection Agency and no Earth Day to celebrate. In Europe, Green Parties and advocacy organizations like Greenpeace and Friends of the Earth did not yet exist. The United Nations did not create an Environment Program until 1972.

In contrast, when transgenic GMO seeds arrived in the mid-1990s environmental advocacy groups like Greenpeace and Friends of the Earth were powerful enough of push back immediately, warning of the damage the seeds might bring. If grown in an open environment, pollen drift might transfer an herbicide resistance trait into wild relatives, and *Bt* corn pollen drifting onto milkweed might kill the larvae of monarch butterflies. Science academies, including those in Europe, were all able by 2004 to refute these environmental fears (DeFrancesco, 2013; Nicolia, et al., 2013), but by then popular perceptions had been turned against GMOs.. In 2010, even the Research Directorate of the EU concluded that "biotechnology, and in particular GMOs, are not per se more risky than e.g., conventional plant breeding technologies," but this judgment also came too late to alter public perceptions.

9. No simple way to detect the altered genetics?

As a sixth point of comparison, there was no simple means to detect the altered genetics of the Green Revolution seeds, other than by growing them. In contrast, GMO seeds carried physically detectable transgenes. Experienced farmers may be able to distinguish between the seeds of different traditional wheat varieties, like Hard Red Spring versus Soft Red Winter, but the seeds of the dwarfed Green Revolution varieties were not sufficiently distinctive to stand out as different. This meant governments would find it hard to block them. GMO seeds and plants, on the other hand, were easier to block because they can be physically tested for the presence of either the transgenes themselves or the associated proteins. Watch-dog NGOs looking for GMO "contamination" can use lateral-flow test strips that detect the presence of proteins produced by GMO crops at a cost of only $4-$6 per test (Villar, 2001). Equipment is also available to perform rapid on-site detection of GMO DNA, with PCR-quality results within minutes at the point of need, without having to send samples to a lab (Envirologics, 2022).

To summarize, the Green Revolution seeds enjoyed all six of the key uptake advantages, while GMO seeds enjoyed only one of the six. This made the wide uptake of Green Revolution seeds a near certainty, and ensured that GMO seeds would be certain to struggle.

What do we learn when we extend this approach to the current case of genome-edited crops, developed in the past decade using tools such as CRISPR?

10. Predicting an uptake trajectory for gene-edited crops

For gene-edited crops, at least three of the six success factors are firmly in place, two others are present but less firm, and a sixth has so far been absent. This predicts a faster spread for gene-edited crops than for GMO crops, but not as fast or wide as for the original Green Revolution seeds.

When scientists first mastered genome editing in 2012 there was far less social agreement on the urgent need to produce more food than in the late 1960s, but more than when GMOs came along in the 1990s. The increased media attention to climate change nurtured an idea that new crop technologies would be needed to cope with more extreme drought, heat, and flood conditions, and genome editing was promoted by scientists as one pathway to make such improvements. For example, a review published in 2021 emphasized that gene editing had already shown promise for boosting abiotic stress tolerance in important food crops, including salinity and drought tolerance in rice, and drought tolerance in maize (Karavolias,et al., 2021).

Social support for increasing food production was also boosted when FAO estimates of food insecurity began to rise in 2014, and even more when four countries were formally declared "at risk of famine" in 2017. The 2020–21 global COVID-19 pandemic and the higher international food prices triggered by Russia's invasion of Ukraine early in 2022 added fuel to the fire. In June 2022 the UN Secretary General, Antonio Guterres, issued a dire warning:

We face an unprecedented global hunger crisis…According to the World Food Programme (WFP), in the past two years, the number of severely food–insecure people around the world has more than doubled to 276 million. There is a real risk that multiple famines will be declared in 2022. And 2023 could be even worse…This year's food access issues could become next year's global food shortage. No country will be immune to the social and economic repercussions of such a catastrophe (UN 2022a).

In the end multiple famines were not declared in 2022, and international food prices fell back down soon after the Secretary General spoke, so these food crisis worries were nothing like the severe and extended Malthusian panic of the 1960s and 1970s, but they did provide a more favorable social context for new crop science in contrast to the deep complacency of the 1990s.

Regarding the second key success factor, an unresolved issue with genome-edited seeds is whether farmers will see immediate and obvious benefits. It is still too early to know the balance between consumer traits and agronomic traits in the application of this new crop improvement method. One inventory of 80 gene-edited crop varieties in the research pipeline in the United States found that over half were intended for product quality or longer shelf-life, rather than for the agronomic properties of greatest interest to growers (Pray, 2022). The first gene-edited soybean variety commercially cultivated in the United States was developed for improved oil quality. The gene-edited tomato variety introduced in Japan contained high levels of gamma-aminobutyric acid (GABA), an amino acid believed to facilitate relaxation and help lower blood pressure (ISAAA, 2021). In Argentina, the largest category of gene-edited crops have been those that deliver "health benefits for consumers." (Whelan,et al., 2020).

Moving to the third key issue, social trust in the institutions developing and delivering gene-edited crops, here we find something far closer to the Green Revolution ideal than to the GMO-era nightmare. Genome editing methods like CRISPR are much faster and cheaper than transgenic GMO methods, so the science can more easily be done outside of the corporate labs that breed mistrust. Professor Jennifer A. Doudna, the Nobel Laureate whose research into RNA biology at Berkeley led to the discovery of the CRISPR-Cas9 gene editing tool, asserts that due to reduced costs and a shortened development timeline, CRISPR "stands out as a powerful democratizing tool which can be used by scientists globally."(FAO, 2022, p. v.) Doudna herself has created an Innovative Genomics Institute, and has joined with the African Union and an African Plant Breeding Academy in launching an African CRISPR course to spread mastery of this new science to local researchers on the Continent. Meanwhile, other not-for-profit developers of this new technology have signaled a parallel intent not to hoard the benefits. Wageningen University in the Netherlands, a world leader in agricultural research, has announced it will waive its patent rights on CRISPR technologies for non-commercial use, to spread research opportunities and help get benefits more quickly into the hands of the poor (Van der Oost and Fresco, 2021).

The commercial control of patented genome-edited crops could remain more restricted in countries that permit seed patents, but private companies may be willing to share them on a royalty-free basis for humanitarian purposes, as some have done for GMO crops in Africa. Even under corporate control, as long as regulatory systems do not create insurmountable approval barriers, the technology is likely to see widespread use. Some precautionary scholars suspicious of the "democratization" narrative even worry that in corporate hands the technology will spread too quickly and in the wrong direction (Montenegro de Wit, 2020). This would be unfortunate, but it does not challenge our view that the technology is likely to see wide use in farm fields.

As another positive factor, food safety fears have largely been missing for gene-edited crops. Advocacy groups in the EU used legal channels to strike a blow against gene-edited crops in the European Court in 2018, placing them under the GMO Directive, but this outcome was not driven by popular food safety sentiments. Some popular mistrust of CRISPR did arise over its potential use in human reproduction to create "designer babies," and campaigns to block this use arose in Switzerland and France as early as 2016. These campaigns were strengthened after a rogue Chinese scientist announced in November 2018 that he had already used CRISPR to edit human embryos (Cyranoski, 2020). But gene-edited crop plants have failed, so far, to trigger widespread popular food safety fears.

In one 2021 survey, 2,800 US consumers were asked to list their concerns if they were offered gene-edited table grapes. Their top three concerns were taste, appearance, and pesticide residues, not the gene-editing process (WSU, 2023). Because most CRISPR crops will contain no "foreign DNA" it will be harder for critics to depict them as dangerous "frankenfoods." In a 2022 report on *Gene Editing and Agri-Food Systems*, FAO concluded that the edited plants classified as SDN-1 products, with no exogenous DNA, would probably have the same "potential risk scope" as natural mutations (FAO, 2022). Even the European Commission reached this benign conclusion, saying in 2021 that new genomic techniques (NGTs) using CRISPR, created "no new hazards" compared with "conventional breeding."(European Parliament, 2021).

As a less positive consideration, CRISPR crops did attract early criticism from prominent European environmental groups including Friends of the Earth and Greenpeace, which sought to depict them as "GMO 2.0." When the Government of France passed a law exempting gene-edited crops from regulations under the EU's GMO Directive, Friends of the Earth, joined by French agricultural associations, filed a lawsuit that eventually went to the European Court of Justice. During the deliberations, the advocate general for the ECJ argued that organisms should be exempt from the GMO Directive if they contained no added foreign DNA, but in July 2018 the full court rejected this advice and issued a surprise ruling that gene-edited crops *would* have to be regulated like GMOs (Stockstad, 2018).

This court decision dealt a heavy blow to CRISPR crops in Europe, but it came from a narrowly confined legal process, not from the kind of popular mobilization that had earlier led European governments to stifle GMOs. To the extent that wider environmental opposition emerged to CRISPR in Europe, it was linked to the gene-editing of people or animals, such as gene-drive edited mosquitoes, not to plants. Organic farmers joined in this opposition because they didn't want gene-edited crops to qualify for organic certification, but their motive was more to protect a brand than to protect the environment. Uncredentialed activists have tried to depict gene-edited crops as dangerous on health and environmental grounds (Robbins, 2021), but media coverage of such efforts has remained scant.

Moving to the final success factor, perhaps the most important similarity between Green Revolution seeds and most CRISPR seeds is the lack of a simple means to detect their altered genetics. This by itself can discourage governments from efforts to restrict their uptake. The 2018 EU court ruling tried to ignore this detectability issue, but it was soon confirmed as a problem in a 2021 report from the EU Reference Laboratory and the European Network of GM Laboratories. This report said it will be extremely difficult for laboratories to detect the presence of unauthorised genome-edited plant products entering the EU market, saying "the polymerase chain reaction (PCR)-based screening methods commonly used to detect conventional GMOs cannot be applied to, nor could they be developed for, genome-edited plant products." (European Parliament, 2021) DNA sequencing might be able to detect specific DNA alterations in a product, but even this would not confirm genome-editing, since the same alteration could have been caused either by conventional breeding or through traditional random mutagenesis methods.

As summarized in Fig. 2, the factors to enable a widespread uptake of genome-edited crops by farmers are therefore not as numerous or strong as they were for the original Green Revolution seeds, but they are significantly more positive than they were for transgenic GMO crops. The imperative for more food production is a bit weaker than it was in the 1960s and 1970s, and opposition to CRISPR crops has arisen from some environmental organizations, but these new crops will have the advantage of coming from highly trusted institutions, they have so far triggered few food safety fears, and since they are extremely difficult to detect they will be nearly impossible for regulators to banish from the marketplace.

A reasonable expectation for the future, then, will a regulatory environment permitting a widespread uptake of genome-edited crops, including in countries that decided earlier to restrict the commercial planting of transgenic GMO crops. A country-by-country regulatory review suggests that this expectation, so far, is being met.

11. Regulatory responses country-by-country

It will be up to national governments to regulate the uptake of genome-edited crops within their own borders. If they follow the 2018 EU lead and try to regulate these crops in the same way they regulate GMOs, uptake will be constrained. Only a few countries have followed the EU lead so far, and many more have not. Important countries that earlier followed Europe's lead in restricting transgenic GMO crops are

	Green Revolution	Transgenic GMOs	Genome-editing
Social agreement on an urgent need to boost food production	Yes	No	Some
Benefits to farmers that are obvious and immediate	Yes	Yes	Few so far
Social trust in the institutions producing and delivering the new seeds	Yes	No	Yes
Absence of new consumer food safety concerns	Yes	No	Yes
Absence of opposition from environmental organizations.	Yes	No	No, but opposition is weak so far
Absence of a simple means to detect the altered genetics of the new seeds.	Yes	No	Yes

Fig. 2. Success factors for crop science uptake by farmers in three cases.

breaking from this pattern in their treatment of genome-edited crops.

11.1. Countries following the EU

One country now regulating gene-edited crops as GMOs is New Zealand, and it is doing so thanks to a surprise court decision, just like in the EU itself. New Zealand's Environmental Protection Authority had originally likened gene-edited crops to those developed through chemical mutagenesis, a category excluded from national GMO regulations, but this approach was blocked by New Zealand's High Court which decided gene-edited crops could not be excluded (FAO, 2022).

In Switzerland a different kind of reversal is now underway. The Federal Council originally declared that gene-edited organisms fell under the definition of GMOs according to national law, but then in March 2022, the Swiss Parliament decided to exempt genome editing from this GMO classification if no foreign DNA had been introduced, and if there was a clear benefit for farmers (Buchholzer and Frommer, 2022). The government is expected to propose separate rules for gene-edited crops by 2024, probably less stringent than for GMO crops (SWI, 2022).

Surprisingly, the Republic of South Africa has followed Europe's lead by regulating gene-edited crops like GMOs. On the other hand, the RSA has a long and nearly unique history of approving and planting several different kinds of GMO crops, not just feed and industrial crops but also staple food crops like GMO white maize, so this decision won't necessarily restrict the planting of gene-edited crops in the RSA. This nation's significant reliance on agricultural exports to Europe may be one reason it decided in 2021 to follow what was then the EU regulatory approach.

Norway also adopted EU authorization procedures for CRISPR crops, which was unsurprising for this strongly anti-GMO country, but its rules are now in flux. Following parliamentary debate and public surveys, Norway's Biotechnology Advisory Board recommended exempting some categories of gene-edited organisms from GMO regulations, or otherwise expediting their approval (FAO, 2022).

11.2. Countries not following the EU

A much larger number of countries have decided not to regulate gene-edited CRISPR crops like GMOs. Many of these are the same Western Hemisphere countries that earlier took a more permissive approach to approving at least some transgenic GMO crops, including the United States, Canada, Argentina, Brazil, and Chile. In 2015, Argentina's Ministry of Agriculture laid out a procedure for classifying gene-edited plants and animals as non-GMO, based on the absence of "novel combinations of genetic material." Chile, Brazil, Guatemala, Honduras, Ecuador, and Paraguay followed Argentina's example. Columbia did the same, so long as "foreign genetic material" is absent (FAO, 2022). Mexico, which takes a strong stance against GMO food crops (it has only planted GMO cotton), has not yet taken a specific stance on gene-edited crops (USDA, 2021). Canada, as early as 2013, commercialized a gene-edited variety of canola, and the United States, which has 80 gene-edited crop varieties in the pipeline, has been cultivating a gene-edited soybean with improved oil quality (developed using TALENs, rather than CRISPR).(USDA 2022a).

More significant is the fact that prominent non-Western Hemisphere countries which had not commercialized GMO food crops until now decided to create a clear regulatory space for gene-edited crops. Japan, for example, will require that genome-edited crops must be registered, but they do not need to undergo GMO-style safety or environmental testing, and since 2020 Japan has explicitly approved the sale of a genome-edited tomato to consumers. (SWI, 2022).

The two most significant countries in this second category are China and India. Both had approved GMO cotton for planting several decades ago, but no major food or feed crops. China may now be on the verge of allowing the domestic cultivation of GMO maize and soybean, partly as a way to reduce import dependence, but it is investing heavily in genome-editing as well. As of 2018, China had nearly as many CRISPR patent applications and published scientific papers on CRISPR as the United States, and some of the results have been tantalizing. Chinese scientists have learned how to silence a gene that restrains kernel production in corn, possibly resulting in a 10 percent increase in yield (Houser, 2022). Eager to capture such benefits, China's Ministry of Agriculture and Rural Affairs released preliminary guidelines early in 2022 that exempted gene-edited crops from GMO regulations, and lifted the requirements for lengthy field trials, so long as the crops had no "foreign" DNA (Buchholzer and Frommer, 2022).

India is another large country that has not approved any major food or feed crops for cultivation in GMO form—only cotton, and more recently mustard. In 2022, the Government of India explicitly exempted genome edited crops from GMO regulations so long as they were SDN-1 or SDN-2, with no exogenous DNA. India's government institutes are already making significant investments in genome-edited crops. The National Agri-Food Biotechnology Institute (NABI) has developed an edited banana rich in beta carotene, improved wheats, and higher yielding rice (Bhattacharya et al., 2021). Wider private sector participation in crop improvements through genome editing will become possible once a licensing regime is sorted out.

In May 2022, the Philippines issued a regulatory framework for gene-edited crops, excluding them from GMO regulations as long as they do not have a novel combination of genetic materials (the Argentine approach). Even Russia, which enacted a law in 2016 prohibiting the cultivation of transgenic GMOs, is on the way to exempting gene-edited plants with no foreign DNA from that law. The Russian government launched a $1.7 billion project in 2019 to develop 30 gene-edited plant and animal varieties in the next decade (SWI, 2022).

In sub-Saharan Africa, gene-edited crops are also being distinguished from GMOs, which have scarcely been grown at all on the Continent. For decades, Nigeria and Kenya commercialized no GMO crops at all. Only recently has Nigeria approved transgenic cotton and cowpea, and in 2023 Kenya's court issued a ruling to permit GMO maize imports. Both Nigeria and Kenya are now giving a green light to CRISPR, publishing guidelines for scientists indicating that crops and animals without a new combination of genetic materials need not be regulated as GMOs, and Kenya's Biosafety Authority has granted approval to seven different gene-editing research projects. Other governments on the Continent will likely follow the Nigerian and Kenyan lead.

12. What to expect in the EU

If gene-edited CRISPR crops with no novel genetic combinations or foreign DNA come to be exempted from GMO regulations in the significant list of countries just mentioned, European Union officials will face an acute dilemma. Will they still attempt to enforce the 2018 ECJ decision, ignoring both the practical challenges and the strong objections they will encounter from trade partners, from Europe's own scientists, and also from European farmers, food companies, and regulators? Or will they find a way to weaken or reverse the Court decision?

The Court's decision was unpopular from the start in the eyes of European business groups, scientists, and regulatory agencies. In April 2019, 22 European business organizations called on member states and the EU Commission to make legislative changes in the GMO Directive to create more space for innovative plant-breeding methods. These companies also warned that the Court ruling would be virtually impossible to enforce, since so many gene-edited products would be indistinguishable from products developed through conventional breeding (ES, 2019). European seed companies also made it clear that if the GMO Directive wasn't changed, or if the Court ruling was not reversed, they would have little incentive to develop gene edited crops for European markets.

The European Food Safety Authority also challenged the Court ruling on substantive grounds, saying it had found "no new hazards" from CRISPR crops (EFSA, 2020), and the European Academies Science Advisory Council (EASAC), representing the science academies of all twenty-eight EU member states, called the Court decision a "setback for cutting-edge science and innovation in the EU."(Euractiv, 2018) In a parallel move, the Group of Chief Scientific Advisors to the EU Commission recommended that the GMO Directive be revised "to reflect current knowledge…on gene editing" (Fortuna, 2019). This pressured the Council of the European Union to ask the Commission to study the barriers to gene editing that might emerge from the court decision.

The Commission finally produced this requested report on "new genomic techniques" (NGTs) in April 2021, endorsing the scientifically obvious view that techniques such as CRISPR had potential "to contribute to sustainable agri-food systems." The Commission's report also conceded that Europe's existing regulatory framework would have "a negative impact on EU public and private research and innovation in NGTs." But the Commission lacked the power to change either the Directive or the ECJ decision. It proposed instead a "wide-ranging communication effort to share the results of the study, to discuss its outcome and next steps with the EU institutions and stakeholders in dedicated meetings" (European Commission, 2021).

After two years, in July 2023, the Commission took a bolder step. It submitted a draft proposal to the Council and the European Parliament that would exempt gene-edited plants from the current GMO directive if they were genetically equivalent to what could be accomplished with conventional plant breeding (Stockstad 2023). Equivalence would be determined by showing that no more than 20 nucleotides had been added or replaced during the gene editing. The proposal requires that gene-edited seeds be labeled as such, and registered in a public database, and herbicide-resistance traits are proposed to be excluded from the relaxed regulation, in deference to European environmental organizations seeking sharp reductions in herbicide use (Stockstad 2023).

If this draft becomes European law it would be a major move toward enabling the use of CRISPR crops, not just in Europe but among Europe's trade partners as well. Still, it would have been cleaner for the Commission just to propose amending the GMO Directive (2001/18/EC) to exclude NGTs, a solution earlier suggested by the Dutch government (Eriksson 2020). Following the UK path would be another option. The UK left the EU in 2020, but it does not want to separate completely from EU regulations. Yet it wants to go forward with gene-edited crops, so it has been moving ahead with new legislation to exempt gene-edited crops from GMO field trial requirements if they could have been created conventionally, and eventually to exempt them from strict case-by-case approval processes as well (Buchholzer land Frommer 2022).

Legislative changes of this kind are relatively easy for the UK, but in Europe amending existing law requires formal agreement by both the European Council and the European Parliament, a high hurdle to clear. A majority vote needed in the European Parliament might eventually be attainable, but in the Council several member states have already indicated they do not want a "watering down" of the regulations for approving GMOs, so the qualified majority needed in the Council to make a change will be difficult to secure (Purnhagen and Wesseler, 2021). If these efforts stall, and if Europe's regulatory isolation from the rest of the world becomes more acute, an alternative path might be to re-litigate the issue by bringing a new case back to the ECJ, framed in a manner more likely to favor gene editing (Purnhagen, 2019).

13. Locking in bias against transgenic GMOs?

While the immediate concern is creating greater space for gene-edited crops to go forward, there are risks attached to doing that by tweaking the definition of what is or is not a "GMO." If GMOs are defined to exclude organisms with "no exogenous DNA" and organisms lacking "novel combinations of genetic material," that will make possible the more reasonable regulation of gene-edited crops, but it will lock in place today's highly precautionary regulations on transgenic crops. Genome editing may then go forward, but earlier transgenic methods with demonstrated potential for crop improvement will remain on the shelf in most countries, especially for staple food crops, and the practical benefits that might come in the future from combining transgenic and CRISPR methods will be sacrificed.

Also, new problems will arise when science delivers its next breakthrough method for plant genetic improvement. The definition of what is *not* a GMO will then have to be amended once more, to clear away unwanted regulatory barriers and avert trade disputes. A far better approach will be to stop building regulations around constantly evolving methods of crop improvement. The more durable solution is to evaluate and regulate the *results* of these improvements, in terms of new risks to human health and the environment. Regulating actual product risks without reference to plant breeding methods allows good science to go forward, free from arbitrary GMO definitions certain to become obsolete when new methods are discovered.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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