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Featured Article

Role of New Plant Breeding Technologies for Food Security and Sustainable Agricultural Development

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Abstract *New plant breeding technologies (NPBTs), including genetically modified and gene-edited crops, offer large potentials for sustainable agricultural development and food security while addressing shortcomings of the Green Revolution. This article reviews potentials, risks, and actually observed impacts of NPBTs. Regulatory aspects are also discussed. While the science is exciting and some clear benefits are already observable, overregulation and public misperceptions may obstruct efficient development and use of NPBTs. Overregulation is particularly observed in Europe, but also affects developing countries in Africa and Asia, which could benefit the most from NPBTs. Regulatory reforms and a more science-based public debate are required.*

Key words: biotechnology, climate change, CRISPR, GMOs, sustainable farming.

JEL codes: O33, Q16, Q57.

Introduction

More than 800 million people worldwide are chronically hungry, and 2 billion are micronutrient-deficient (FAO 2019a). Food insecurity and low dietary quality cause huge public health problems. Malnutrition is responsible for physical and mental development impairments, various infectious diseases, and unacceptably high numbers of premature deaths (Development Initiatives 2018). Reducing these problems and achieving Sustainable Development Goal 2, "zero hunger and improved nutrition," requires major transformations in global food systems. Isolated fixes cannot solve the complex issues (Meemken and Qaim 2018; Springmann et al. 2018; FAO 2019a). Among other strategies, agricultural technologies have a very important role to play.

Producing enough food for a growing population has always been a challenge since humans became sedentary and started agriculture some 12,000 years ago. This challenge is not yet overcome, as the global population continues to grow. Fertile land and water are becoming scarce, so production increases have to come primarily from yield and productivity growth (Cai, Golub, and Hertel 2017). Plant breeding has contributed to considerable yield growth, especially during the last 100 years (Huang, Pray, and Rozelle 2002; Evenson and Gollin 2003). In addition, massive increases in the use of chemical fertilizers, pesticides, irrigation water, and other yield-enhancing inputs have helped to raise food production and feed the rising population. Even though chronic hunger is still widespread in many developing countries, the global proportion of hungry people was reduced from over 50% in the first half of the twentieth century to around 11% today (FAO 2019a).

However, the increasing intensity of agricultural production also has its problems. The high use of agrochemicals combined with unsustainable agronomic practices has led to several environmental externalities. Agriculture also contributes to climate change, accounting for about 25% of the global greenhouse gas emissions (IPCC 2019). And climate change will likely affect agricultural production negatively through increasing mean temperatures, heat and water stress, and rising frequencies of weather extremes. Poor people in Africa and Asia will be hit hardest by climate calamities, not only because these people are particularly vulnerable to price and income shocks, but also because many of them depend on agriculture for their livelihoods (Wheeler and von Braun 2013). Without new types of technologies, sustainable agriculture and food security cannot become reality any time soon.

New plant breeding technologies (NPBTs), including genetically modified organisms (GMOs) and gene-edited crops, could possibly be a game changer (Zilberman, Holland, and Trilnick 2018; Zaidi et al. 2019). They could contribute to higher crop yields, lower use of chemical fertilizers and pesticides, better crop resilience to climate stress, reduced postharvest losses, and more nutritious foods (Bailey-Serres et al. 2019; Eshed and Lippman 2019; Zaidi et al. 2019). However, NPBTs are not yet widely used and accepted. Transgenic GMOs in particular are often seen very critically (Greenpeace 2015). Even though 30 years of research and commercial applications suggest that GMOs are not more risky than conventionally bred crops (EASAC 2013; NAS 2016; German National Academy of Sciences Leopoldina 2019), there continue to be widespread concerns about possible negative health and environmental consequences. These concerns have led to safety regulations that are much stricter for GMOs than for any other agricultural technology (Qaim 2016). Given that most of the GMOs commercialized up till now were developed by large multinational companies, there are also economic and social concerns related to market power and unequal benefit distribution (Stone 2010).[1] Similar concerns have also been voiced for the more recent gene-edited crops (Shew et al. 2018). This review article provides an overview of the potentials, risks, and actually observed impacts of NPBTs with a particular emphasis on their role for food security and sustainable agricultural development.

[1]*As will be argued below, public concerns about the safety of GMOs and related regulatory hurdles for their commercialization have contributed to the market dominance of a few multinationals, because only large companies can afford the costly regulatory procedures.*

Plant Breeding and Food Security: Historical Trends

Since the beginnings of agriculture some 12,000 years ago, farmers in different parts of the world have tried to increase crop production through selecting the highest-yielding plants for multiplication, developing new tools, and testing various agronomic practices. Successful innovations were adopted more widely, and some of the technologies and practices also spilled over to other parts of the world. Until the nineteenth century, this process of innovation was slow. Most agricultural production increases came from expanding the agricultural land area, not from increases in crop yields. Hunger and undernutrition were widespread. Even in Western Europe, the majority of the population was suffering from food insecurity and insufficient access to calories and nutrients until the nineteenth century (Fogel 1989). In the late eighteenth century, Thomas Robert Malthus, a British cleric and economist, predicted widespread famine, because the population and food demand grew faster than the possibility to expand the land area for food production (Malthus 1789).

The race between population growth and food production entered a new era in the second half of the nineteenth century. Agricultural research became more scientific. New insights into plant genetics, plant nutrition, and advancements in the chemical industry speeded up the process of agricultural innovation substantially. The development and spread of improved crop varieties and the use of chemical fertilizers and other modern inputs led to massive increases in agricultural productivity in the USA and Europe during the first half of the twentieth century (Qaim 2016). As a result, food insecurity and undernutrition declined rapidly in the USA and Europe. However, it took a while until modern technologies were adapted and used more widely also in poorer countries. In the 1950s and 1960s, population growth outpaced food production especially in Asia, leading to serious concerns about looming famines.

Green Revolution

The Rockefeller Foundation and other development organizations were instrumental in launching several public sector research programs aimed at adapting new agricultural technologies to tropical and subtropical conditions and make them available to farmers in the developing world. Since the late 1960s, high-yielding varieties of wheat and rice, and later also maize, developed through these international programs were widely adopted by farmers in Asia and Latin America (Evenson and Gollin 2003). Combined with a rise in the use of irrigation, fertilizers, and other agrochemicals these new varieties contributed to a doubling and tripling of agricultural yields within a relatively short period of time (Qaim 2017). These technological developments and the resulting increase in food production became widely known as the Green Revolution. Due to various constraints, the Green Revolution was less pronounced in Africa (Eicher and Staatz 1984).[2]

The production increases in major staple foods through the Green Revolution improved the availability and affordability of calories. This is especially

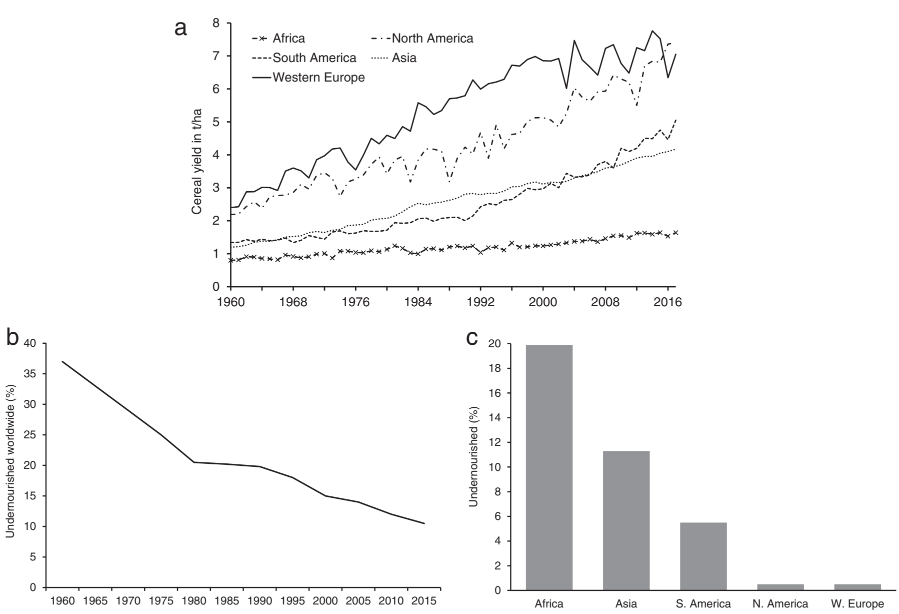
[2] *In the early days of the Green Revolution, especially high-yielding varieties of wheat and rice were developed, both of which are not among the key staple foods in large parts of Africa. In addition, roads and irrigation infrastructure, which are important to get access to needed complementary inputs and benefit from the new varieties, were less developed in Africa than in Asia and Latin America.*

relevant for poor population segments that typically spend a large proportion of their income on food. Simulations demonstrate that mean consumption levels of calories in developing countries would have been 10–15% lower had the high-yielding varieties of wheat, rice, and maize not been introduced (Evenson and Gollin 2003). Thus, the Green Revolution has contributed significantly to reducing hunger in Asia and Latin America. The predicted famines were prevented and poverty rates declined considerably (Eicher and Staatz 1984; Evenson and Gollin 2003). Norman Borlaug, the chief wheat breeder of the Rockefeller Program in the 1960s and often referred to as "the father of the Green Revolution" received the Nobel Peace Prize in 1970 for his contribution to increasing world food supplies and food security.

Figure 1 shows developments in agricultural production and food security since the 1960s. With increasing crop yields (figure 1*a*), the proportion of undernourished people declined from close to 40% in 1960 to 11% today (figure 1*b*). Increasing yields did not only increase food availability, but also agricultural profits and incomes in the small farm sector, which is home to the majority of the world's poor and undernourished people (Fan et al. 2005; Qaim 2017). With this close association between crop yield trends and food security in mind, it is not surprising to see that the prevalence of hunger today is still much higher in Africa than in other regions (figure 1*c*). In Africa, agricultural productivity growth was much slower than elsewhere and could not keep pace with the rising population. Africa is the only region worldwide where the number of hungry people is still increasing (FAO 2019a).

The growth in cereal yields over the last few decades is the result of progress in plant breeding, more intensive use of fertilizers, pesticides, and irrigation water, and several other factors. Disentangling the contribution of individual factors to yield growth is difficult, due to synergies and complexities in establishing the correct reference trend (Olmstead and Rhode 2008;

Figure 1 Global trends in agricultural productivity and hunger. (*a*) Mean cereal yields by region, 1960–2017. (*b*) Prevalence of undernourishment worldwide, 1960–2015. (*c*) Prevalence of undernourishment by region, 2018. *Source*: Based on data from FAO (2019a, 2019b).



Huffman, Jin, and Xu 2018). However, the role of plant breeding seems to have increased over time. It is estimated that breeding contributed to around 20% of the yield growth between 1960 and 1980, and to 50% of the yield growth between 1980 and 2000 (Evenson and Gollin 2003; Qaim 2016). Given that further increases in the use of fertilizer and other inputs are associated with decreasing marginal yield effects, the role of plant breeding and plant genetics for agricultural productivity will likely continue to grow over time.

Problems with the Green Revolution

While the Green Revolution contributed to agricultural growth and hunger reduction, it also brought about several problems and did not sufficiently address others. Some of the problems are related to environmental effects. The high-yielding varieties of the Green Revolution were performing particularly well under irrigated conditions and were much more responsive to fertilizers than traditional landraces. Some of the new varieties were also more susceptible to certain pests and diseases. Hence, farmers' use of irrigation water, chemical fertilizers, and pesticides strongly increased. The overuse of these inputs in some regions has led to falling groundwater tables, soil and water pollution, nitrous oxide emissions, and other environmental issues (Foley et al. 2011).

The effects of the Green Revolution on biodiversity are more complex. The intensive use of agrochemicals has reduced biodiversity in agricultural landscapes. Furthermore, as the productivity growth concentrated on a relatively small number of high-yielding varieties of wheat, rice, and maize, species diversity and varietal diversity in global agricultural production and food supplies declined (Khoury et al. 2014; Pingali 2015). On the other hand, higher yields on the cultivated land reduced the need for additional cropland expansion, thus preserving natural biodiversity. While agricultural intensification can contribute to local cropland expansion under certain conditions, studies show that the Green Revolution's technology-driven yield growth was land saving at the global level and helped to preserve millions of hectares of forestland and other natural habitats (Villoria 2019). As land-use change is also the biggest source of greenhouse gas emissions from agriculture (IPCC 2019), land-saving technological change helps to reduce the climate change effects of agricultural production as well.

The human nutrition effects of the Green Revolution also had several dimensions. While reductions in hunger and food insecurity are undisputed, impacts on other forms of malnutrition were less positive. As mentioned, the strong focus of the Green Revolution on only a few major cereals led to lower species diversity in farming and food supplies, which also had implications for dietary diversity. Whereas prices for cereals decreased, more nutritious foods—such as pulses, vegetables, fruits, and animal source products—became relatively more expensive (Gomez *et al*. 2013; Qaim 2017).[3] In addition, plant breeders' strong attention to yield was at the expense of nutritional traits, resulting in lower micronutrient contents in high-yielding cereal varieties (DeFries et al. 2015). Against this background, it is not surprising that micronutrient deficiencies declined much more slowly than calorie undernutrition in recent decades (Gödecke, Stein, and Qaim 2018).

[3]*Changing relative prices have led to a substitution away from more nutritious foods. On the other hand, decreasing prices for staple foods had a positive income effect, which may also have increased the consumption of more nutritious foods. The net effects are situation specific.*

As the world population continues to grow, further food production increases will be required in the future. However, future production increases need to be more diverse and more environmentally friendly. This will require novel agronomic and breeding approaches. The role of NPBTs in this connection is discussed in subsequent sections.

New Plant Breeding Technologies

The last 30 years have seen a revolution in plant genetics and the development and use of new breeding technologies. In this section, we briefly describe some technical aspects of NPBTs, before discussing concrete breeding objectives and technological risks in subsequent sections.

Genetically Modified Organisms (GMOs)

A GMO is an organism into which genes coding for desirable traits have been inserted through the process of genetic engineering (Qaim 2009). Plant breeders depend on genetic variation for the development of new, useful crop varieties. To increase genetic variability in a particular species, breeders have—for a long time—used wide crosses, hybridization, mutagenesis induced by radiation or chemical agents, and other techniques, which can lead to fairly random outcomes. GMOs have opened new horizons, as the genetic variation available for breeding has become much larger. With recombinant DNA techniques, individual genes coding for desirable traits can be introduced to the plant without simultaneously making all the other genetic changes that occur through conventional crossbreeding or traditionally induced mutagenesis. GMO crops are often referred to as transgenic crops, implying that foreign genes—so-called transgenes—were introduced (Qaim 2016).

One fundamental difference between conventional and transgenic plant breeding is the product of the research. The product of conventional breeding is a new variety that has certain desirable characteristics and can be used by farmers in the particular environment for which it was developed. The product of transgenic research in contrast is not one particular new variety, but a new trait, which can then be introduced or backcrossed into many local varieties. Thus, in principle, GMO technologies can help to preserve varietal diversity (Krishna, Qaim, and Zilberman 2016). With certain adjustments, the same traits can also be transferred to other species. This can be of particular advantage for vegetatively propagated crops, such as banana and cassava, which are difficult to improve through conventional crossbreeding (Qaim 2016).

Transgenic GMOs have been developed since the 1980s and were first commercialized in a few countries in the mid-1990s. The most widely used GMO traits thus far involve herbicide tolerance and insect resistance. Effects of GMO adoption are discussed in more detail below.

Gene Editing

Transgenic research techniques, as used since the 1980s, have increased the precision of plant breeding considerably. However, the gene transfer mechanisms used to develop the first-generation GMOs could not predetermine the exact location of the transgenes in the recipient plant. Hence, when using these first-generation transfer mechanisms, numerous transgenic events had to be created and tested in order to later select those that express the desired trait successfully without undesired off-target effects. During the last 15 years, new DNA sequencing methods have facilitated the mapping of relevant regions of the plant genome, thus contributing to a considerable further improvement in breeding precision and speed (Hickey et al. 2019). Based on these methods, new breeding technologies were developed for which the term "gene editing" (also "genome editing") is now widely used (Kumawat et al. 2019).

Gene editing refers to techniques in which DNA is inserted, modified, replaced, or deleted in the genome of a living organism at predetermined locations. Targeted genetic scissors are used to create site-specific double-strand breaks, which are then repaired using the cell's own repair systems. Different gene-editing methods are used, including zinc finger, TALEN, and the nowadays most widely used CRISPR/Cas system that was developed in 2012 (Kumawat et al. 2019; Schindele, Dorn, and Puchta 2019). Gene-editing techniques are not only used in plants, but also in animals to breed for desirable traits, and in humans to detect and repair genetic diseases. Gene editing is a very dynamic field of research with further improved methods constantly emerging (Hickey et al. 2019). Recently, the so-called prime-editing system was developed, which builds on a single-strand break and further adds to breeding precision (Anzalone et al. 2019).

The genetic changes made with gene-editing techniques may involve simple or complex mutations or also the integration of species-specific and foreign genes. Most of the gene-edited crops developed so far involve simple point mutations without the integration of foreign DNA, meaning that the resulting crop plants do not carry any transgenes (Zaidi et al. 2019). Gene-edited crops with simple point mutations have new desirable traits, but it is hardly possible for outsiders to detect that they were actually gene edited; identical point mutations could in principle also occur naturally or through traditional mutagenesis (Grohmann et al. 2019).

Breeding Objectives with NPBTs

The breeding objectives pursued with NPBTs are not completely different from those pursued with conventional breeding. However, the much larger genetic variation that can now be exploited and the direct integration or modification of genes and gene sequences increases breeding efficiency and the development of certain traits and plant features that were previously difficult or impossible to obtain. Specific traits always have to be combined with locally adapted germplasm, which is usually the result of conventional breeding. Hence, NPBTs are a complement, not a substitute for conventional breeding. In the following, I provide a short overview of traits that biotechnologists currently try to develop or that have already been tested and used in the field.

Pest and Disease Resistance

One important category of traits involves pest and disease resistance. Among the first GMOs used in agriculture were insect-resistant crops into which bacterial genes from *Bacillus thuringiensis* (Bt) were introduced. Furthermore, virus resistance, fungus resistance, and bacterial resistance are important traits that have been developed with transgenic and nontransgenic gene editing in a number of crop species, including several cereals as well as cassava, banana, papaya, and a number of vegetables (Oliva et al. 2019; Zaidi et al. 2019). Pest- and disease-resistant crops can reduce chemical pesticide sprays and increase effective yields through lower crop losses (Qaim and Zilberman 2003; Bailey-Serres et al. 2019).

Other Agronomic Traits

Many research groups are also working on higher crop resilience to abiotic stress such as heat, drought, flooding, and soil salinity – traits that are particularly important to make agriculture more climate smart (Hickey et al. 2019). Transgenic and gene-editing technologies are being used to develop tolerance to abiotic stress in maize, rice, wheat, beans, and several other crop species (Eshed and Lippman 2019; Kumawat et al. 2019).

Substantial advances have recently also been made in developing crops with higher nutrient use efficiency (Bailey-Serres et al. 2019). Crop yields are heavily dependent on sufficient availability of nutrients, especially nitrogen and phosphorous, currently provided primarily through chemical fertilizers. Higher nutrient use efficiency can increase crop yields with lower amounts of fertilizers, thus reducing energy use and the environmental footprint of agricultural production. Researchers also use transgenic and nontransgenic techniques to raise the yield potential of crop plants through increasing plant growth and photosynthetic efficiency. While the genetic mechanisms determining yield can be complex, recent studies showed that also relatively simple site-specific modifications can lead to significant yield growth regardless of the growing conditions (Wu et al. 2019).

Product Quality

Researchers are also working on various traits to improve product quality. Several fruits and vegetables with CRISPR/Cas-based nonbrowning traits are already on the market in North and South America. Such technologies could help to reduce food losses and waste. NPBTs are also used to change the fatty acid composition of oil crops, reduce the gluten content of wheat, or increase the micronutrient content of various food crops, all of which could have positive human health effects (De Steur et al. 2012; Modrzejewski et al. 2019).

New Domestication and Crop Diversity

Gene-editing technologies can also be used to domesticate neglected crops and wild plants in a short period of time, an approach that has been termed "de novo domestication" (Fernie and Yan 2019). Traditionally, the domestication of plants and the development of productive varieties required decades of breeding, which is also the main reason why most breeding programs during the last 100 years concentrated on the further improvement of a relatively small number of crops that were domesticated already several thousand years ago. The recent discovery of multiple key domestication genes and scientific breakthroughs in introducing multiple genomic changes in plants simultaneously with CRISPR/Cas enables the domestication of wild species within a single plant generation (Schindele, Dorn, and Puchta 2019). De novo domestication can contribute to enhancing agrobiodiversity and dietary diversity with possible benefits for the environment and human nutrition (Singh et al. 2019).

Gene editing can also be used for the redomestication of already domesticated crops. During the history of crop domestication, the selection and breeding for higher yield, and the international exchange of germplasm, many local resistance and resilience genes of wild species were lost or never fully integrated into breeding lines (Fernie and Yan 2019). In other words, the gene pool in wild relatives of domesticated plants is often much bigger than the genes and traits in the domesticated gene pool (Hickey et al. 2019). Instead of trying to integrate certain traits from wild relatives into modern varieties retrospectively, redomestication may be a more efficient option in some cases, helping to increase genetic diversity within crop species and make agriculture more climate-resilient, locally adapted, and less dependent on chemical inputs.

Speed Breeding

That gene editing is much faster than any other breeding method and that it can be efficiently applied to all kinds of species, including previously neglected and not even domesticated ones, is a key advantage against the background of global environmental change. Changing climates do not only contribute to shifting weather patterns and more frequent weather extremes but also to evolving pathogen populations, so that the ability to rapidly adapt crop plants and agricultural production to the changing conditions is crucial to ensure future food and nutrition security (Bailey-Serres et al. 2019; Hickey et al. 2019). Another big advantage is that gene editing is relatively cheap and easy to implement; so it can also be used by smaller labs and companies, which could contribute to more diversity and competition in seed markets.

Technological Risks

Every new crop variety that is released into the environment and consumed by humans and animals may be associated with certain risks. Broadly speaking, two different types of risk can be distinguished. First, possible risks related to the breeding process. Second, possible risks related to the particular traits developed. Thirty years of risk research related to GMO crops suggest that there are no new risks related to the breeding process. While off-target effects occur, these are easily detected and can be eliminated during the testing phase. In other words, GMOs are not inherently more risky than conventionally bred crop varieties (EASAC 2013; NAS 2016; German National Academy of Sciences Leopoldina 2019). This conclusion was drawn by all major science academies and by various international organizations, including the World Health Organization (WHO) and the Food and Agriculture Organization (FAO).

Based on the scientific evidence available there is no justification to regulate GMOs differently than conventionally bred crops. In reality, however, there are huge differences in regulation. For the approval of a new GMO, many years of molecular, biochemical, and environmental testing, as well as feeding trials, are required. Some precaution when dealing with new technologies is always advisable. But GMOs are not so new anymore; they have been widely used and consumed for 25 years without a single case of harm to human health or unexpected environmental effects. GMOs are the most highly regulated and tested foods in the world. Many crop varieties that are commonly used in conventional and organic agriculture would not have been approved if the same standards that are now used for GMOs had applied (Qaim 2016).

For gene-editing technologies such as CRISPR/Cas a long safety record is not yet available, because these technologies have only been used for a few years. However, the point mutations developed so far are genetically indistinguishable from natural mutations or traditional mutagenesis (Grohmann et al. 2019), so new types of risk cannot be expected. Gene editing can also lead to off-target effects, but the frequency of off-target effects is much lower than for transgenic GMOs and for traditional mutagenesis (Holme, Gregersen, and Brinch-Psersen 2019).

The second type of risk, namely risks related to a particular new trait, is different. Such risks exist, but they cannot be assessed for GMOs or gene-edited crops in general. Each new trait can have different effects. Herbicide tolerance, for instance, will differ in its environmental and health impact from traits such as drought tolerance or increased vitamin levels. Trait-specific risks can only be assessed case by case, which is also true for conventionally bred crops. Hence, a trait-based (also called product-based) regulatory approach would make much more sense than the process-based approach used for GMOs in most countries.

For gene-edited crops, regulatory approaches are still evolving. Many countries, including the USA and Australia, have decided to not regulate gene-edited crops as GMOs, meaning that gene-edited crops are regulated in the same way as conventionally bred crops, unless they contain foreign DNA. This is different in the European Union (EU). The EU Court of Justice decided in 2018 that gene-edited crops are automatically considered GMOs, meaning that the same strict rules and regulatory procedures as used for transgenic crops apply (Holme, Gregersen, and Brinch-Psersen 2019). Further implications are discussed below.

Effects of NPBTs on Sustainable Development

Gene-edited crops are not yet widely used in agricultural production, so effects on economic, social, and environmental development cannot yet be observed. However, GMOs have been used for 25 years, and a large number of adoption and impact studies exist.

Adoption of GMOs

The commercial application of GMOs began in the mid-1990s. Since then, the technology has spread rapidly around the world, both in industrialized and developing countries. Since 2011, the area grown with GMOs in developing countries has been larger than the area in industrialized countries. In 2018, GMOs were planted on 192 million ha, equivalent to 14% of the total worldwide cropland. These 192 million ha were grown by 17 million farmers in 26 countries (ISAAA 2018). Most of these countries are located in North and South America, followed by Asia. In Europe and Africa, very few countries have adopted GMOs, which is mostly due to limited public acceptance in these regions and unfavorable regulatory environments (Qaim 2016). The countries with the biggest shares of the total GMO area in 2018 were the USA (39%), Brazil (27%), and Argentina (12%), followed by Canada (7%), India (6%), Paraguay (2%), China (2%), Pakistan (1%), South Africa (1%), and a number of other countries (ISAAA 2018).

In spite of the widespread international use of GMOs, the portfolio of available crop-trait combinations is still very limited. While many different traits were developed and tested, most of them were not yet approved for commercial use. So far, only a few concrete GMO technologies have been commercialized. The dominant technology is herbicide tolerance (HT) in soybeans, which is mostly used in North and South America. In 2018, HT soybeans accounted for almost 80% of total worldwide soybean production. Other widely used GMO crops include insect-resistant (IR) maize and cotton. The insect-resistance trait is based on Bt genes, which control stemborers, rootworms, and cotton bollworms. Especially Bt cotton is grown in many different parts of the world, including by smallholder farmers. In 2018, India had the largest Bt cotton area, followed by the USA, China, Pakistan, and various other developing countries (ISAAA 2018).

Effects of GMO Adoption

Over the last 25 years, many studies have been conducted, analyzing the effects of GMO adoption on crop yield, pesticide use, farm profits, and other outcomes in different parts of the world. A meta-analysis has evaluated these existing studies, finding that GMO adoption benefits farmers in most situations (Klümper and Qaim 2014). On average, GMOs have increased crop yields by 22% and reduced chemical pesticide quantities by 37% (Table 1). GMO seeds are usually more expensive than conventional seeds, but the additional seed costs are more than compensated by savings in chemical pest control and higher revenues from crop sales. Average profit gains for adopting farmers are 68%.

A breakdown of GMO impacts by modified trait reveals a few notable differences (Table 1). IR crops lead to a significant reduction in pesticide quantity, whereas HT crops do not in many situations. Such differences are expected. IR crops protect themselves against certain insect pests, so that spraying insecticides can be reduced. HT crops are not protected against pests but against broad-spectrum chemical herbicides (mostly glyphosate), which can facilitate weed control. While HT crops have reduced herbicide quantity in some situations, they have contributed to notable increases in the use of broad-spectrum herbicides elsewhere. Average yield effects are also higher for IR than for HT crops.

A breakdown by region shows that farmers in developing countries benefit more from GMO adoption than farmers in industrialized countries (Table 1). The reasons are twofold. First, farmers operating in tropical and subtropical climates often suffer from higher pest damage that can be reduced through GMO adoption. Hence, effective yield gains tend to be higher than for farmers operating in temperate zones. Second, most GMOs are not patented in developing countries, so that seed prices are lower than in industrialized countries, where patent protection is much more common (Qaim 2016).

Table 1 Mean Impact of GMO Crop Adoption (Meta-Analysis Results)

	Yield	**Pesticide quantity**	**Farm profit**
All GMO crops	+22%	–37%	+68%
By modified trait			
Herbicide tolerance (HT)	+9%	+2%	+64%
Insect resistance (IR)	+25%	–42%	+69%
By region			
Industrialized countries	+8%	–18%	+34%
Developing countries	+29%	–42%	+78%

Source*: Based on data from Klümper and Qaim (2014).*

Beyond the benefits for farmers, GMOs have also contributed to positive environmental and health effects (Barrows, Sexton, and Zilberman 2014). Reductions in the use chemical pesticides through IR crops have led to benefits for biodiversity and ecosystem functions and to a lower exposure of farmers, farm workers, and consumers to toxic substances. HT crops have facilitated the adoption of reduced-tillage practices, thus curbing erosion problems and greenhouse gas emissions (Smyth, Phillips, and Castle 2014). Finally, without the productivity gains from GMOs during recent years, around 25 million hectares of additional farmland would have to be cultivated globally, in order to maintain current agricultural production levels (Qaim 2016). As mentioned, farmland expansion is an important contributing factor to biodiversity loss and climate change (IPCC 2019).

However, especially the widespread use of HT crops in North and South America is also associated with certain environmental problems. Higher profits and easier weed control have induced many farmers to narrow down their crop rotations, now often growing HT crops as monocultures. This has contributed to resistance development in weed populations and increases in other pest and disease problems, sometimes leading to higher pesticide use (Fernandez-Cornejo et al. 2014). These environmental problems are not inherent to GMOs; they are the result of inappropriate technology usage. Conventionally bred HT crops, which are used in some countries, can lead to the same types of environmental problems if not used properly. Improved seeds, regardless of whether they were bred conventionally or with NPBTs, should never be considered a substitute for good agronomic practice, but should be integrated into sound and locally adapted crop rotations and agricultural systems.

GMOs and Smallholder Farmers

New technologies that are suitable also for smallholder farmers can contribute to poverty reduction and broader rural development. Hence, it is important to understand whether crops developed with NPBTs can be used successfully by smallholder farmers. Some experience with GMOs exists. Again, it is important to differentiate by crops and traits. HT soybeans have so far been used primarily by large farms in North and South America. Soybeans are not much grown by smallholders. Moreover, weed control in the small farm sector is often conducted manually. This underlines that not every GMO crop-trait combination is well suited to the small farm sector.

However, IR crops with inbuilt Bt genes are widely grown by smallholder farmers in countries like India, China, Pakistan, and South Africa (ISAAA 2018). The example of Bt cotton in India is particularly interesting, because anti-biotech activists repeatedly claimed that GMOs have ruined smallholder cotton growers in India. These claims were shown to be wrong (Gilbert 2013; Qaim 2016). Smallholder cotton growers in India have rapidly adopted Bt cotton because the technology is very beneficial for them. Within less than 10 years after its first commercialization, more than 90% of the cotton growers had switched to GMO seeds.

Impact estimates with four rounds of panel survey data from India, spanning a time period of eight years, showed that Bt cotton adoption has significantly and sustainably reduced chemical pesticide applications, leading to large health and environmental benefits (Table 2). Smallholders typically apply pesticides manually with backpack sprayers and no protective devices.

Table 2 Impact of Bt Cotton Adoption in India (Panel Data Evidence)

	Mean effect
Economic effects	
Effect on cotton yield	+24%
Effect on cotton profit	+50%
Effect on farm household living standard	+18%
Environmental effects	
Effect on chemical insecticide use	−44%
Effect on pesticide environmental impact	−53%
Nutrition and health effects	
Effect on pesticide poisoning incidences	−28%
Effect on calorie consumption	+5%
Effect on micronutrient consumption	+7%
Effect on food insecurity	−20%

Source*: Based on data from Kouser and Qaim (2011), Kathage and Qaim (2012), Krishna and Qaim (2012), Qaim and Kouser (2013), and Veettil, Krishna, and Qaim (2017).*

The reduction in spaying intensity has lowered the incidence and severity of pesticide poisoning considerably. Higher yields and profits through Bt cotton adoption have also contributed to income gains, raising living standards by 18% on average. As a result, improvements in dietary quality and nutrition were observed. GMO adoption has reduced food insecurity among Indian cotton growers by 20% (Table 2).

Beyond cotton growers, other rural households in India have benefited from growth in the cotton sector through additional employment. This is particularly relevant for landless laborers, who often belong to the poorest of the poor. Two-thirds of all rural income gains from Bt cotton adoption in India accrue to poor people with incomes of less than $2 a day (Qaim 2016).

Similar to these results from India, Bt cotton adoption has also contributed to poverty reduction and other social benefits in the small farm sectors of China, Pakistan, South Africa, and several other developing countries (Qaim 2009; Huang et al. 2010; Qiao 2015; Kouser, Spielman, and Qaim 2019). Bt maize has been used successfully for many years by smallholders in South Africa and the Philippines (Smyth, Phillips, and Castle 2014). A more recent application of GMO technology in a local food crop is Bt eggplant in Bangladesh, which also contributes significantly to lower insecticide use and higher yields and incomes among smallholder vegetable growers (Ahmed et al. 2019).

Future NPBT Applications

In addition to HT and IR crops, various other GMO applications are being used commercially, so far on smaller areas, including virus-resistant beans in Brazil, virus-resistant papaya in Hawaii, and drought-tolerant maize in the American Midwest. Transgenic drought-tolerant maize has also been tested for several years in Africa but was not yet commercially approved. Field trials with a number of other GMO crops and traits have been carried out on various continents, including nitrogen-efficient rice, fungus-resistant potato, and sorghum and cassava with higher micronutrient contents (Qaim 2016; Wesseler et al. 2017).

Transgenic Golden Rice with high contents of provitamin A has been tested for many years and was recently—after multiple delays—approved for seed multiplication and use in the Philippines. Golden Rice may soon also be commercialized in Bangladesh and other countries of Asia, where vitamin A deficiency is a serious health issue. Ex ante impact studies show that Golden Rice—if widely consumed—could significantly reduce child mortality, infectious diseases, and eyesight problems in developing countries (Stein, Sachdev, and Qaim 2008; Wesseler and Zilberman 2014). Golden Rice is probably the technology that has been blocked most intensively by anti-biotech groups, because these groups fear that a GMO that helps the poorest of the poor in particular could undermine their narrative of biotech only serving the interests of large multinational companies (Regis 2019).

Examples of gene-edited crops at or near the end of the research pipeline are manifold, including fungus-resistant wheat, rice, banana, and cacao; drought-tolerant rice, maize, and soybean; bacterial-resistant rice and banana; salt-tolerant rice; and virus-resistant cassava and banana, among others (Hickey et al. 2019; Tripathi, Ntui, and Tripathi 2019; Zaidi et al. 2019). Many of these technologies could contribute significantly to sustainable agricultural development and food security.

Regulation and Public Perceptions

As explained in the previous section, the cultivation of GMOs has increased rapidly since the mid-1990s. However, of the 192 million ha grown with GMOs in 2018, over 95% were grown with only four different species (soybean, maize, cotton, and canola) and two modified traits (HT and IR). This narrow focus of already commercialized GMO applications has different reasons. One reason is that many crop traits are somewhat more complex to develop than HT and IR, meaning that more research and testing is required. However, a much more important reason for the narrow crop and trait focus in commercialized applications is the low public acceptance of GMOs and, related to this, the complex biosafety and food safety regulatory procedures. As mentioned, several other GMOs were extensively tested but not yet approved for commercial use, because of overly precautious regulators, highly politicized policy processes, and extensive lobbying efforts of anti-biotech activist groups (Herring and Paarlberg 2016).

Public Perceptions

Especially in Europe, GMOs—when used in food and agriculture—have a very negative image. Many Europeans are deeply convinced that transgenic GMOs are very risky for human health and the environment. There is a widespread notion that the foreign genes introduced to the crop plants may lead to unexpected negative effects, either immediately or in the long run. Furthermore, as most GMOs were developed by large multinational companies, many in the wider public are also concerned about a monopolization of seeds and food supply chains with negative social consequences, especially in developing countries. And, as several of the biotech multinationals have a history of producing and selling chemical pesticides, it is also widely believed that GMOs would promote and perpetuate unsustainable agricultural systems with increasing pesticide use.

Where do these negative attitudes stem from? When the work with recombinant DNA started in the 1970s (at that time mostly with viruses, not plants), little was known about the safety of the resulting transgenic organisms. Scientists themselves recommended a precautious approach, and this suggestion was adopted in the design of regulatory policies (Fagerström et al. 2012). Many countries developed specific policies for GMOs, which are much stricter than for other types of technologies. When the first open field trials with transgenic plants started in the late 1980s and early 1990s, environmental NGOs became active in opposing GMOs, sometimes with spectacular campaigns. These NGO campaigns reinforced public fears of uncontrollable risks.

But why do these fears persist 30 years later, in spite of the mounting scientific evidence that GMOs are not riskier than conventionally bred crops? One of the reasons is that scientists are often not the ones who the public trusts most. Environmental NGOs are often trusted more, as it is believed that they are fighting for the good without any hidden agenda. But for some of the NGOs, campaigning against GMOs has become a business model and a good source of donation revenues. As a result, the NGO narratives about GMOs never changed, even when it became clear that many of the arguments used are completely wrong.

The mass media also played their role in perpetuating negative public attitudes about GMOs. In their approach to provide a "balanced picture," journalists often contrast findings by researchers with statements by NGO representatives. For media users, hearing the same types of NGO arguments and narratives again and again can perpetuate beliefs and contribute to confirmation bias up to a point where new scientific evidence is hardly entering the public debate anymore.

A manifest example of the strong role of environmental NGOs in forming and perpetuating public beliefs about GMOs and of the difficulty to enter science into the debate is an open letter that more than 100 living Nobel laureates wrote to Greenpeace in 2016 (Roberts 2018). In the letter, the Nobel laureates urged Greenpeace to end its opposition to GMOs because the arguments used for so many years had all been debunked by scientific evidence. Greenpeace's simple answer was that the Nobel laureates were not experts in the field of food and agriculture. The instance was hardly covered in the mass media.

As mentioned, attitudes towards GMOs are particularly negative in Europe, but European attitudes have spilled over to other parts of the world as well, including Africa and Asia (Herring and Paarlberg 2016). Policymakers and the wider public in Africa and Asia are not only influenced by NGO narratives, but also by concrete concerns of losing export markets when adopting GMOs that are not approved for import in the European Union.

Gene-edited crops are still much newer. Up till now, most of them do not contain foreign DNA, which means that public attitudes may, in principle, be much more positive (Zaidi et al. 2019). Many of the public reservations against GMOs are related to the fact that they contain foreign genes. However, public knowledge about gene-edited crops is still quite limited, and several environmental NGOs have started to frame these new technologies as the industry's attempt to introduce GMOs through the backdoor. These NGO activities are not helpful for forming public opinions based on objective information.

Safety Regulation

As mentioned, GMOs are more heavily regulated than any other agricultural technology. The regulation focuses primarily on the assessment and management of biosafety and food safety risks. Risk assessment and risk analysis is governed by internationally accepted guidelines developed by the Codex Alimentarius. Nevertheless, significant differences in the regulatory approaches exist between countries. Differences between the US American and the EU approaches are particularly pronounced (Qaim 2016). In the USA, GMOs—while requiring additional tests—are regulated under the same laws that are also used for conventional agricultural technologies. If the required tests for known risks have been passed successfully, there is no further regulatory hurdle for commercialization of the GMO in question. In contrast, in the EU specific laws were introduced, requiring a separate testing and approval process for GMOs that is overseen by institutions especially established for this purpose. And there is no automatism for approval when all tests have been passed. Instead, politicians from the EU Commission and the EU member countries have to finally approve all GMO applications. Following the precautionary principle, EU politicians can refuse to approve GMO crops on grounds of uncertainty alone, even without any evidence of risk (Qaim 2016).

As EU politicians know how unpopular GMOs are in many of the member countries, the scientific risk assessments are regularly ignored and approvals are delayed or denied. Only one single GMO crop event is currently authorized in the EU for commercial cultivation, namely a Bt maize event that was approved back in 1998 (for comparison, around 200 GMO crop events were approved in North and South American countries during the last 25 years). And even this old Bt maize technology was later prohibited in several of the EU member countries (Smyth, Philipps, and Kerr 2016). In other words, the process-based regulatory approach, together with the precautionary principle and the heavily politicized regulatory practice, is effectively a ban on GMO crop technologies in Europe. The approach does not only suppress commercial use, but also the development of new GMO crops, as also field trials need to be authorized. When such approvals are not issued on time, or when field trials are vandalized, as happened repeatedly in the past, GMO crop and trait developments can be seriously delayed or thwarted altogether. In July 2018, the EU Court of Justice ruled that all gene-edited crops fall under the same GMO laws and procedures (Holme, Gregersen, and Brinch-Psersen 2019). Science academies have urged politicians to reform the EU GMO legislation (German National Academy of Sciences Leopoldina 2019), but the political will to do so seems limited.

The EU regulatory procedures stifle the development and use of NPBTs in Europe and elsewhere. Many countries in Africa and Asia have copied European-style regulatory approaches for GMOs. And GMO events also need approval when not intended for cultivation in Europe but only imported as food or feed. As the EU is a big importer of agricultural commodities, the slow and politicized approval procedures hamper the use of GMOs also in exporting countries. Even in India and China, where Bt cotton has been used successfully for many years, major GMO food crops have not yet been approved and used commercially (Pray et al. 2018).

The reluctance of policymakers to approve GMOs is largely driven by low consumer acceptance. On the other hand, the fact that GMOs are not approved by policymakers reinforces widespread public beliefs that the technology is inherently dangerous (Herman, Fedorova, and Storer 2019). The lengthy procedures also make the commercialization of GMOs unnecessarily expensive, thus contributing to consolidation and market power in the seed industry and discouraging the use of NPBTs to develop crops and traits with smaller commercial market potentials. Some of the societal resistance against

GMOs is based on the argument that the promises are oversold, because so far only very few concrete technologies are actually available on the market. Fears are also related to GMO seeds being dominated by a few multinationals. The mutually reinforcing combination of false NGO narratives, public misperceptions, and costly overregulation is clearly the main reason for the observed industry concentration and the fact that many of the exciting technological potentials have not yet materialized.

Other Regulations for NPBTs

Beyond biosafety and food safety, a number of other regulations are relevant for NPBTs. Especially in Europe, the approach of singling out GMOs as something very different requires a number of rules that enable the coexistence of GMO systems, conventional systems, and organic systems in agricultural production, trade, processing, and retailing. GMO foods have to be labeled as such. In addition to this mandatory labeling, voluntary labeling of foods as derived from GMO-free supply chains also exists in Europe and elsewhere. More details about the economics of GMO labeling and coexistence can be found in McCluskey, Wesseler, and Winfree (2018) and Zilberman, Holland, and Trilnick (2018).

Another important area of biotech regulation is the protection of intellectual property rights (IPRs). The ability to obtain patent protection on biological inventions differs between countries. In the USA, patents on genes, genetic processes, and GMO plant varieties have proliferated since the 1980s (Clancy and Moschini 2017). Most of these patents are held by a few multinational companies, which is also one of the reasons for the public opposition to GMO crops. First, there are widespread ethical concerns with patenting life and genetic materials that exist in nature. Second, there are social concerns, because it is feared that patents lead to seed monopolies and corporate control of the food chain. Indeed, too strong and far-reaching patent protection on genes and enabling technologies reduces the freedom to operate in research and can contribute to market concentration (Deconinck Forthcoming). Efficient forms of IPR protection for NPBTs, which properly balance research incentives, freedom to operate, and social benefits, may still have to be developed, also taking into account that many gene-edited varieties are genetically indistinguishable from conventionally bred crops. However, widespread fears that patents will inevitably hurt developing countries and lead to exploitation of smallholder farmers seem to be overrated, because patent protection is part of national law, and so far most plant biotechnologies are not patent-protected in developing countries (Qaim 2016).

Conclusion

NPBTs offer large potentials to contribute to sustainable agricultural development and food security. Plant breeding and the adoption of high-yielding varieties played a key role in reducing hunger over the last 100 years. However, the Green Revolution technologies of the past focused on a small range of cereal crops and performed particularly well under favorable environmental conditions and high input regimes. This has led to narrowing agricultural and dietary diversity and—in some situations—also to environmental problems associated with excessive agrochemical input use. NPBTs, including GMOs and gene-edited crops, can help to further increase yields, while addressing the shortcomings of Green Revolution technologies. NPBTs can help to increase crop diversity, raise yield potentials, provide better resistance to pests and diseases, increase nutrient use efficiency, make crops more resilient to climate shocks, and improve nutritional quality, just to name a few of the types of technologies that plant biotechnologists have already worked on extensively. A few GMO crops were already widely adopted with clear economic, social, and environmental benefits, including in the small farm sector of developing countries.

Of course, sustainable food and nutrition security requires more than NPBTs. But against the background of further population growth, climate change, and a dwindling natural resource base it would be irresponsible to not harness the potentials that modern plant biotechnology offers. Currently, overregulation and public misperceptions stirred and perpetuated by consistently false NGO narratives about risks obstruct the way for more efficient development and use of NPBTs. Especially in Europe, serious regulatory reforms and a more honest and science-based public debate are required. The European skepticism has also influenced many developing countries in Africa and Asia, which could benefit the most from using NPBTs. Developing countries are well advised to disregard European attitudes and use GMOs and gene-edited crops more confidently for the benefit of their farmers and consumers.

This plea in favor of NPBTs does not mean that everything will be fine without public regulation and policies. Like any transformative technology, NPBTs raise certain questions that need to be addressed to avoid undesirable side effects. Some of these questions are correctly raised by biotech critics, but the conclusion that any potential issue would justify a technology ban is certainly inappropriate. Unfortunately, in many countries the entrenched fundamental debate about banning or allowing GMOs has overshadowed more detailed discussions about suitable technology management.

Relevant questions, for which policy responses and institutional adjustments will be required, include the following. How can we ensure that newly developed crop varieties with desirable traits are used sustainably as part of diverse agricultural systems and not as substitutes for proper agronomy? How can market power by a few multinationals be prevented? How can we facilitate the development of new crops and traits that may not have huge commercial potential but may be particularly beneficial for poor farmers and consumers? How can we ensure that suitable new crop technologies will actually reach the poor through favorable technology transfer mechanisms? What is the appropriate level of IPR protection in industrialized and developing countries? Finding answers to these and other relevant questions will require more research and a more constructive public and policy dialogue.

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