Chapter 40
GMOs and Sustainable Agriculture

Sheldon Krimsky

Abstract The introduction of genetically engineered crops in agriculture in the mid-1990s has been heralded as the advent of the Second Green Revolution. Among the expectations were high yields, fewer inputs like pesticides, and new nutritionally enhanced foods. Around the same period that traditional breeding was eclipsed by molecular breeding, the concept of sustainability was introduced into the working lexicon of many disciplines, practitioners, and corporations. This chapter discusses the principles of sustainability and their applications to agriculture, evaluates specific GMOs against the criteria for sustainable agriculture, and argues that GMO crops must be understood within an agro-ecological system.

Keywords GMOs · Sustainable Agriculture · Agro-ecological systems · Sustainability · Ethics

Introduction

Agriculture had its origins in the Middle East between 10,000–12,000 years ago in the region called Mesopotamia also referred to as the Fertile Crescent, which covered parts of modern-day Syria, Lebanon, Jordan, Israel, and Northern Egypt. Up until that time, human societies were organized around hunting and gathering. Sustainable agriculture was introduced as a concept in 1987 with the publication of *Our Common Future* also known as the Brundtland Report, issued by the World Commission on Environment and Development of United Nations. The Commission

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Sheldon Krimsky died before publication of this work was completed.

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was chaired by Norwegian Prime Minister Gro Harlem Brundtland. The application of biotechnology through recombinant DNA techniques to produce food crops was introduced in the mid-1990s. Large scale agriculture began its transition from traditional breeding, which included selection, exposure of plant cells to radiation and chemical mutagens, and hybridization, to molecular breeding, which included genetic modification or genetic editing, applying CRISPR (clustered regularly interspaced short palindromic repeats) to plant cells for creating desirable traits.

The introduction of genetically engineered seeds, beginning with insect resistant and herbicide tolerant crops brought international opposition from environmental groups like Greenpeace as well as several nations. In response to the controversy over genetically modified organisms (GMOs) introduced into agriculture, the European Union established a regulatory system that included risk analysis, testing programs, and restricted criteria for adoption of GMOs into agricultural production and in GMO food shipments to European nations. In contrast, the United States did not require testing but began with the assumption of "substantial equivalence." Unless otherwise proven, the U.S. regulatory agencies considered GMOs as safe as traditionally bred crops and that the process utilizing recombinant DNA techniques or gene editing was not a factor in assessing risks.

While new biotechnology products were entering the farming sector, the interest in sustainability had been growing globally, in part spurred on by an awareness of climate change, the pollution of oceans, the loss of biodiversity, the decline in soil quality, and the rise in the use of agro-chemicals. The United States and Brazil were world leaders in the use of GMOs in large scale agriculture. Most of their staple crops of corn and soybeans consisted of GMOs. With such large sectors of the agricultural economy devoted to GMOs, agricultural scientists and environmentalists began to ask whether GMO applications was or could be consistent with sustainable agriculture. By the new millennium, this question began to receive serious attention. This paper will explore the issue of GMOs and sustainability first outlining some core principles in sustainable agriculture, and then exploring whether GMO agriculture meets these standards and how one can answer that question.

Principles of Sustainable Agriculture

The terms sustainable or sustainability are among the most widely used terms in the title of scientific papers. From Web of Science, I found 122,744 titles containing one of those two words. In 2021 and 2020 the terms were found in 14,896 and 20,760 titles in scientific papers, respectively, while 19,255 books had the root "sustainable" in their titles. Before we can ask "Is X sustainable," where X is a product, system, or technology we must be clear about what we mean when people use the term "sustainability." (Shearman, 1990: 1–8). Some believe the term is kept deliberately ambiguous to satisfy stakeholders with different political and economic agendas. We can begin by examining how the term has been used in agriculture.

The Brundtland Report referred to sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Specifically, with respect to sustainable agriculture the report states:

> …rapid growth combined with deteriorating income distribution may be worse than slower growth combined with redistribution in favour of the poor. For instance, in many developing countries the introduction of large-scale commercial agriculture may produce revenue rapidly but may also dispossess many small farmers and make income distribution more inequitable. In the long run, such a path may not be sustainable; it impoverishes many people and can increase pressures on the natural resource base through over commercialized agriculture and through the marginalization of subsistence farmers. Relying more on smallholder cultivation may be slower at first, but more easily sustained over the long term.

It also states that the rate of depletion of topsoil, fish stock and forest resources should not exceed the rate of regeneration. The operative term is "regenerative agriculture" also referred to as "sustainable agriculture." Practitioners of sustainable agriculture seek to integrate three main objectives into their work: a healthy environment, economic profitability, and social and economic equity. I shall use as guiding points that promoting sustainable agriculture means advancing agroecology, protecting the resource base of natural systems (maintenance of natural assets) for future generations including and especially the soil, protecting plant and animal species biodiversity, and enhancing the quality of life and health for farmers, farm workers and society. When we ask: "will the technology of genetically modified organisms (crops) support agricultural sustainability, we shall refer to these contributing factors".

These factors may be interpreted differently by different scholars and stakeholders. Constance (2010) noted: "because the concept of sustainability is deeply contested, agribusiness is able to exploit the ambiguity surrounding the definition of sustainable and exercise power in attempts to frame sustainable agriculture in their favor." Also, we can find a different emphasis in the literature on the core factors of sustainable agriculture. Gaffney et al. (2019) emphasize four factors: ensure production of an adequate food supply; alleviate poverty; achieve better nutrition; and conserve natural resources, which must be balanced against one another (Gaffney et al., 2019).

Sustainability is rooted in the living world's moral obligation to future generations. Our obligation to future generations falls into four archetypal positions. The first and strongest obligation I refer to as "family values" because it seeks to make future generations better off than the current generation. This is reminiscent of the parental exhortation "we want our children to be better off than their parents." The second moral position is that we want to ensure that the next generation is no worse off than the current generation. This viewpoint implies that we wish to protect biodiversity, natural resources, sources of energy, the climate so that the next generation can experience life as comparable to how it is experienced by the current generation.

The third position is to ensure that future generations have the knowledge to address the problems of scarcity and loss of raw materials, species or what we consider a favorable climate. I call this the knowledge-based response to our obligation to future generations. We do not know who these people will be or what their needs and desires will be, so fulfill our obligation to them by ensuring that the knowledge we preserve and transmit will guide them to a favorable future. Regarding preserving resources, this position places our obligation only to the current generation of people. Finally, the fourth position extends beyond the knowledge-based response by placing no restrictions on our consumption or depletion of natural resources nor does it obligate us to create a survival knowledge for future societies. This is the position of pure hedonism, with no obligations to the future. It is sometimes referred to as "cornucopian." Consume what you want without any moral constraints. Future generations will find their own path.

Within these archetypal positions, sustainability is associated with position #2, ensuring that future generations are not worse off than we are. For sustainable agriculture this means protecting the soil (soil conservations), preserving wildlife, maintaining forests, and protecting the biodiversity of the planet as well as the climate for human habitation.

Building on the Brundtland criteria for sustainable development, Karlsson (2003) proposed three ethical principles for GMO sustainability. Karlsson echoes the three cornerstones of sustainability: environmental, economic, and social. His ethical principles are process, rather than outcome- based. The first is the Precautionary Principle. Applied to GMOs it means that the lack of scientific certainty of the adverse effects of a living genetically modified organism on the food or the environment for which there is credible concern, shall not be used stop the health and environmental assessment in favor of release. The second principle is commonly known as "The Polluter Pays." The responsibility for the costs of preventative action on a GMO, including risk assessment, is placed on the polluter prior to release into the environment. Finally, Karlsson (2003) cites public participation for decisions on risk management as part of the social dimensions of sustainability.

Sustainable Applications of GMOs

Genetically modified organisms (GMOs) include any biological species that is genetically modified in a laboratory (in vitro) by either recombinant DNA molecule technology or the more recently discovered CRISPR (gene editing) technology or any of its variant methods. The technology itself cannot be said to be sustainable or unsustainable without understanding how it is used and the products it has created. There is no inherent reason why GMOs should be used to exacerbate or ameliorate unsustainable agricultural practices. As Russell (2008) has stated: "…it is not feasible to ask whether a particular system, industry or technology is 'sustainable' or 'unsustainable,' but useful to consider whether it is associated with a tendency towards or away from sustainability." (Russell, 2008: 214). Herrero et al. (2015) noted that "agricultural biotechnologies cannot be usefully assessed as isolated and technological entities but need to be evaluated within the context of the broader socio-ecological system that they embody and engineer." Following Russell's analysis that no product or process is inherently sustainable or unsustainable, I shall examine several crops that could progress toward sustainability and in the next section outline several products that are antithetical to sustainable agriculture.

In Hawaii, papaya tree plantations were blighted by the papaya ringspot virus (PRV), which could not be controlled by pesticides or netting to stop its spread by the aphid vectors. A laboratory technique initially called "coat-protein gene-mediated transgenic resistance" was developed for papaya cells. A protein from the capsid coat of a mild form of the PRV was inserted into papaya cells. Under the right conditions, plants can be sensitized with a coat protein of an invading pathogen, which sensitized the plant to induce an immune response (RNA or proteins) against the invading pathogens. In some respects, it is like a vaccination in mammals that induces an immune response against a viral pathogen. Once vaccinated, the animal's immune system remembers the invading virus and can launch an antibody defense.

The GMO papaya has been widely heralded as a success, which can be adapted to any sized farm. Its use mitigates against the use of insecticides and other environmentally damaging methods to destroy the aphids carrying the virus. However, some studies have found effects of the GMO papaya on the soil microorganisms in the rhizosphere (Wei et al., 2006; Phironrit et al., 2007). Thus far these observed effects have not altered the use of GMO papaya in the Hawaiian plantations although other genetic approaches to the PSRV such as RNA silencing have shown favorable outcomes mitigating effects on rhizosphere.

While the GMO papaya is an actual example of a GMO in use, there are also potential applications of transgenic crops that show a favorable approach to sustainability. One of these applications is the genetic modification of bacteria and plants to extend nitrogen fixation to new plants. The massive application of inorganic nitrogen fertilizers in agriculture is a well-documented environmental contaminant. The fertilizers drift away from agricultural fields leaching into lakes, rivers, streams, and aquifers creating eutrophication. The excessive nitrogen sources, providing a richness of nutrients in bodies of water, frequently causes a dense growth of plant life and results in the death of animal life from lack of oxygen.

All plants require nitrogen for growth. There is a small sub-group of plants, including peas, beans, soybeans, alfalfa, clover, and peanuts, which have a symbiotic relationship with soil bacteria that reside at the root nodules of the plants. These bacteria located in the rhizosphere of the plant, called nitrogen-fixing bacteria, can draw nitrogen from the air and make it available to the selected plants. The process is called nitrogen fixation. A set of genes called nif genes are genes that encode enzymes involved in the fixation of atmospheric nitrogen into a form of nitrogen available to living organisms.

One of the earliest projects for the new biotechnology industry during the last quarter of the twentieth century was the transformation of plants that cannot naturally fix nitrogen to become nitrogen fixers. This involved genetically modifying bacteria that are symbiotic to these plants with nif genes or to genetically modify the plants with the nif genes with the role of the bacteria. One of those projects was to turn cereal crops into plants that could utilize nif bacteria.

While creating new plants with nitrogen-fixing properties would contribute to sustainable agriculture, there were many obstacles.

The primary obstacle to expanding nitrogen fixation to non-leguminous plants is the difficulty of restructuring a plant to bear root nodules similar to those of legumes where nitrogen fixation works (Krimsky & Wrubel, 1996).

Research continues to design bacteria to deliver fixed nitrogen to cereal crops. No commercial applications have yet been developed as it has proven more challenging than originally believed (Ryu et al., 2020). Other prospects for social sustainability, or the development of new positive social applications of GMOs, are products that are improved nutritionally without creating any detriment to the environment. The first application of this came with Golden Rice. The rice genome was genetically modified to contain a precursor to vitamin A, which the body can turn into the vitamin. In vitamin A, scarce communities' blindness is common. This product would help reduce the worldwide prevalence of child blindness.

In 2000, the international media proclaimed that a new variety of GMO rice could save the lives of one million children a year. A Swiss scientist Ingo Potrykus had genetically modified the rice endosperm to be beta carotene enriched. Consumption of the rice converts the beta carotene to vitamin A. The idea of beta carotene conversion or biofortification was a new strategy for the biotechnology to elevate the public's acceptance of GMOs. Research into biofortified rice began in 1982 under leadership of the Rockefeller Foundation.

The GMO rice was called "Golden Rice" reflecting its orange carotene color. The availability of Golden Rice to poor developing nations in South Asia and Sub-Saharan Africa where vitamin A deficiency (VAD) was prevalent could in theory prevent countless cases of blindness and death. VAD increases the risk of measles and diarrhea in children. It was estimated that 93% of VAD-related deaths could be traced to those regions.

In nearly 40 years of research into beta carotene-fortified rice, the primary concerns were over its safety and efficacy. Another concern was whether consumers would accept rice of a different color to which they had been accustomed. For the GMO rice to be successful, it had to exhibit a sufficiently high conversion factor from beta carotene to vitamin A in order that standard dietary amounts of rice would prevent VAD.

A sustainable approach to bioconversion would have to ensure that it was safe over a person's lifetime and that the agricultural fields of Golden Rice would be safe for the environment. Some scientists expressed concern that the new beta carotene pathways in rice created by the gene insertion could produce toxic by-products including retinoid compounds.

In 2019 Golden Rice was approved for use as s human food in the Philippines. It was permitted for planting in July 2021. The American Society of Human Nutrition reported that a cup of Golden Rice consumed daily could provide 50 percent of the Recommended Daily Allowance for vitamin A (Tang et al., 2009).

Unsustainable Applications of GMOs

While the examples of GMOs given in the previous section show the possibility that these crops can contribute to sustainable agriculture, the next examples will illustrate how other GMO crops are unsustainable under the criteria discussed in the introduction. One of the earliest GMOs to enter commercial markets were herbicide tolerant crops. The premise behind developing these crops was that they would resist any damage from spraying herbicides, which could then be used to eliminate weedy competitors of the crops.

In 1970 Monsanto synthesized the herbicide glyphosate. It was approved by the Environmental Protection Agency as a broad-spectrum herbicide in 1974. Glyphosate's herbicidal property is based on its inhibition of 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase, the enzyme catalyzing the final step of the shikimate pathway, which is necessary for the plants to synthesize amino acids. Monsanto scientists delivered genes into crop cells that produced proteins which interfered with glyphosate's pathway for inhibiting EPSP synthase, which makes the crops glyphosate tolerant. Corn and soybeans were among the first crops genetically modified to become glyphosate tolerant. Monsanto called these products "Roundup-Ready" seeds. Roundup was its patented formulation of glyphosate.

Glyphosate-based herbicides (GBH) have proven to be highly controversial as they are implicated in causing human cancers and because they have been found detrimental to the environment. In 2015 the International Agency for Research on Cancer (IARC), an independent research arm of the World Health Organization, issued a report that glyphosate is a probable human carcinogen. Other studies have found GBH deleterious to many species, including butterflies, quails, frogs, fish, tadpoles, and soil microorganism (Krimsky, 2021). Given the extensive environmental impacts of GBH and its suspected effects on humans, this class of herbicides does not meet the standards of agricultural sustainability. Thus, the system that GBH is embedded and co-dependent, namely, GMO transgenic crops, cannot be sustainable.

Since the publication of *Silent Spring* by Rachel Carson, the role of insecticides to prevent crop damage has been extensively studied. The impacts of insecticides (or biocides as Carson would call them) on non-target species and its toxicity to humans have been the primary considerations in excluding them from sustainability regimes.

The prospects of genetically engineering plants with insecticidal proteins provided another approach to the management of insects. It has been estimated that 37 percent of what is planted is lost from insect herbivores. In the mid-1970s, scientists discovered a plasmid (circular piece of DNA) in the bacterium *Bacillus thuringiensis* (Bt), which encodes crystalline proteins (more than 200 types) that is toxic to specific insects.

Natural forms of Bt have been used by farmers since the 1920s and was approved in the form of granules or as a liquid under the organic standards as a natural microbial pest control agent. The term Bt-transgenic crops had the insecticidal properties of Bt built into the genome of the plant. The first approved Bt crops were introduced into commercial agriculture in 1995 and included potatoes, corn, and cotton. Its application was expanded to many other crops after the Environmental Protection Agency and the Food and Drug Administration declared that the Bt δ-endotoxin expressed in crops is not hazardous to humans.

The prospect that Bt transgenic crops would substitute for billions of pounds of chemical insecticides that are sprayed promiscuously on farmland leaching into waterways made these GMO crops a prospect for sustainable agriculture. There were several problems that arose from the extensive use of Bt crops. First, insects became resistant to them. Because the presence of Bt endotoxins were on the crops at every stage of growth, the pressure on insects for mutations was great. According to Tabashnik et al. (2013): "The increase in documented cases of resistance likely reflects increases in the area planted to Bt crops, the cumulative duration of pest exposure to Bt crops, the number of pest populations exposed and improved monitoring efforts."

Much has been learned about the effect of Bt crops on non-target species in cases where insects and animals consume the crop and when the breakdown products of the Bt crops leach into water systems. In his dissertation at the University of Bern Yi Chen (2021) wrote:

"even after 100 days, plant-derived Bt protein can be detected in water. These studies indicate that the Bt protein released from remnants of Bt plant tissue remain in water for quite some time. The Bt protein from transgenic crops can get into water through the pollen, rhizosphere secretion, post-harvest crop residues and other forms of diffusion, so that organisms in aquatic ecosystems are principally exposed to Bt protein. The Bt protein can potentially aquatic organisms when they are susceptible to the protein at the encountered concentrations."

Once the insects became resistant to Bt crops, farmers had to either use chemical pesticides or accept crops that had more than one toxic protein. Thus, plants had to be genetically modified to contain a pyramid of toxic proteins, imposing additional risks on the crops and the environment (Huang, 2021). Many of the early gains of reduced insecticide use had diminished. Tabashnik and Carriere (2019) wrote in the *Journal of Economic Entomology* that "the global monitoring data reviewed here reveal 19 cases of practical resistance to Bt crops, which is field-evolved resistance that reduces Bt crop efficacy and has practical consequences for pest control."

Secondly, organic farmers, who used Bt sparingly at the times that insects were invading their crops, could no longer used the pesticide because of the rise of Bt resistant insects. For these reasons, transgenic Bt GMO crops are not likely to be sustainable. Some commentators believe the only limit to Bt crop sustainability is the growth of insect resistance (Glaser & Matten, 2003). But there are other issues affecting sustainability such as the effect of ubiquitous Bt on non-target insects and other arthropods. Notwithstanding the skepticism about BT crop sustainability, there have been very favorable reports. One 2011 report indicated that Bt cotton may serve as an example of how African countries can achieve sustainable agriculture. “Bt cotton increased yields, raised income, saved energy use (increased productivity and economic returns” (Vitale et al., 2011). In contrast, an analysis of GMO sustainability in Switzerland where transgenic crops were reviewed on both socio-economic and environmental sustainability reached an unfavorable conclusion. “Results show that the six out of seven scenarios showed a lower socio-economical sustainability for genetically modified crops compared to conventional systems.” They did report a slight improvement in the environmental component (Wohlfender-Bühler et al., 2016). Question the long-term sustainability of Bt crops. “The evolution of resistance and cross-resistance threaten the sustainability of genetically engineered crops that Bt crops produce insecticidal toxins derived from the bacterium *Bacillus thuringiensis*. And Li et al. question whether Bt crops will be sustainable. “The current trend of increasing proportion of cultivation of transgenic Bt crops is pushing towards dramatic destabilization of the agroecosystem, thus raising sever concerns about the sustainability of transgenic Bt crops as an effective management tool for the control of target insect pests in the future” (Li et al., 2019). The National Research Council issued a report in 2010 on how genetically engineered crops impact farm sustainability stating that “the application of genetic-engineering technology to crops has not developed novel means of pest control, such as developing plant mechanisms to resist pest damage, nor has it reached most minor crops” (National Academies of Sciences, 2010).

Because GMOs cover a wide range of crop phenotypes, including disease resistance, herbicide tolerance, biofortification, a broad-brush assessment of a crop’s contribution to sustainability cannot be made a priori. It must be assessed in the context of the agricultural system. Myhr and Myskja (2018) note:

“With NBTs [new breeding technologies] it may be possible to develop plants that have increased drought and saline tolerance relevant for the developing world. Such gene-edited plants can have positive, stable long-term effects on environment, economic and social conditions, and hence be argued to contribute to sustainability. Conversely, the same plants may also have adverse long-term environmental effects.” Sustainability means more than high yield or improving the commercial value of crops to farmers, but as Azadi et al. (2015) note: sustainability must respect natural resource preservation, biodiversity, and the beauty of the environment, which without an ethical support system cannot compete with agricultural economics.

Conclusions

Sustainable agriculture is not premised on a particular crop of set of crops, but rather on an integrated ecological system. A GMO crop cannot be assessed for its sustainability by itself without considering the system in which it is embedded. While a single crop or procedure cannot turn a non-sustainable agricultural system into a sustainable one, it can turn a sustainable system into a non-sustainable one. This has been shown in the example of glyphosate-based herbicides (GBHs), which are paired with herbicide tolerant crops (i.e., Ready Roundup crops). Even for a sustainable agricultural system, GBHs will turn it into a non-sustainable one.

The ethics behind sustainability is fundamentally in the selection of a system, where all the parts fit together to preserve the ecology for future generations. Some refer to the system as Integrated Pest Management, agro-ecology, or more generally integrated agriculture. The animal systems interact with the crops; the soil microbes interact with the plants; the diversity of crops support stability. Or as Shearman (1990) noted, "sustainability is a concept in search of a framework instead of a definition." Anderson et al. (2019) argue:

> Sustainable, eco-rational IPM strategies rely on a diversified portfolio of tactics, of which GE crops represent a valuable tool. By leveraging the experiences gained with GE crops, understanding the limitations of the technology, and considering the successes of GE traits in IPM plans for different crops and regions, we can enhance the durability and versatility of IPM plans for future crops.

Transgenic crops that work effectively within the integrated system can contribute to sustainable agriculture. Tabashnik and Carriere (2017) state: "Transgenic crops are most desirable when used in combination with other control tactics in integrated pest management. The sustainability of transgenic crops for pest control depends largely on the will to implement this [IPM] knowledge." Azadi et al. (2015) acknowledge the higher productivity of some GMO crops but they assert that "it remains questionable whether GM crops can result in a revolution towards 'agricultural development' and 'sustainability' or make only a significant change in 'agricultural growth'."

What this paper has shown is that GMO use is embedded in a system. If the system meets the criteria of sustainability, the individual GMO may either contribute to or violate the criteria. That can only be decided after a full analysis of each GMO product is completed including how it interacts with the agro-ecological system.

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