Pros and Cons of GMO Crop Farming

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Summary and Keywords

The global area sown to genetically modified (GM) varieties of leading commercial crops (soybean, maize, canola, and cotton) has expanded over 100-fold over two decades. Thirty countries are producing GM crops and just five countries (United States, Brazil, Argentina, Canada, and India) account for almost 90% of the GM production. Only four crops account for 99% of worldwide GM crop area. Almost 100% of GM crops on the market are genetically engineered with herbicide tolerance (HT), and insect resistance (IR) traits. Approximately 70% of cultivated GM crops are HT, and GM HT crops have been credited with facilitating no-tillage and conservation tillage practices that conserve soil moisture and control soil erosion, and that also support carbon sequestration and reduced greenhouse gas emissions. Crop production and productivity increased significantly during the era of the adoption of GM crops; some of this increase can be attributed to GM technology and the yield protection traits that it has made possible even if the GM traits implemented to-date are not yield traits *per se*. GM crops have also been credited with helping to improve farm incomes and reduce pesticide use. Practical concerns around GM crops include the rise of insect pests and weeds that are resistant to pesticides. Other concerns around GM crops include broad seed variety access for farmers and rising seed costs as well as increased dependency on multinational seed companies. Citizens in many countries and especially in European countries are opposed to GM crops and have voiced concerns about possible impacts on human and environmental health. Nonetheless, proponents of GM crops argue that they are needed to enhance worldwide food production. The novelty of the technology and its potential to bring almost any trait into crops mean that there needs to remain dedicated diligence on the part of regulators to ensure that no GM crops are deregulated that may in fact pose risks to human health or the environment. The same will be true for the next wave of new breeding technologies, which include gene editing technologies.

Keywords: genetically modified, herbicide tolerance, insect resistance, trait

Introduction

Genetically modified organisms (GMOs) result from recombinant DNA technology that allows for DNA to be transferred from one organism to another (transgenesis) without the genetic transfer limits of species to species barriers and with successful expression of transferred genes in the receiving organism (Gray, 2001). Four crops, maize, canola, soybean, and cotton, constitute the vast majority of GM crop production (James, 2015A), and GM crops have been grown commercially since 1995 (Bagavathiannan, Julier, Barre, Gulden, & Van Acker, 2010). The acceptance of GM crops by farmers has been rapid, with the global GM production area growing from 1.7 million hectares in 1996 (International Service for the Acquisition of Agri-biotech Applications [ISAAA], 2015) to 182 million hectares in 2014 (James, 2014). Just 10 countries represent almost 98% of the GM hectares worldwide. The top GM producing countries are the United States (73.1 million ha), Brazil (42.2 million ha), Argentina (24.3 million ha), Canada (11.6 million ha), and India (11.6 million ha) (James, 2014). GM soybean is the most popular GM crop and almost 50% of global soybean acres are now GM soybean (James, 2015B). For corn and cotton the global proportion of GM is 30% and 14%, respectively (James, 2015B). GM canola occupies only 5% of the global canola hectares (James, 2015B). GM crops are grown on only 3.7% of the world's total agricultural land, by less than one percent of the world's farmers. Almost 100% of GM crops on the market are either herbicide tolerant (HT) or insect resistant or have both of these two traits (Dill, CaJacob, & Padgette, 2008).

The production of GM crops is not equal across the world and in some jurisdictions there is little or no production. Countries in the European Union (EU) are a notable example in this regard. The near complete moratorium on the production of GM crops in the EU is based on common public view and political decisions rather than GM food safety assessment (Fischer, Ekener-Petersen, Rydhmer, & Edvardsson Björnberg, 2015). This is also true for Switzerland, where, for example, since 2005 GM foods and crops have been banned because of strong negative views on the part of both Swiss farmers and citizens (Mann, 2015). Five EU countries (Spain, Portugal, the Czech Republic, Slovakia and Romania) accounted for 116,870 hectares of Bt maize cultivation in 2015, down 18% from the 143,016 hectares in 2014. The leading EU producer is Spain, with 107,749 hectares of Bt maize in 2015, down 18% from the 131,538 hectares in 2014 (James, 2015A). Russia is the world largest GM-free zone (James, 2015A). Despite the claimed benefits over risks, and the wide adoption of biotech-improved crop varieties in many parts of the world, Europe and Africa still remain largely GM-free in terms of production (Paarlberg, 2008). This may be due in part to the relative absence of reliable public scientific studies on the long-term risks of GM crops and foods and the seed monopoly that is linked to GM technology development (Paarlberg, 2008). In Asia, four countries, including Turkey, have banned GM crops. The GM concerns in Europe have also slowed down the approval of GM crops in many developing countries because of impacts on agricultural exports (Inghelbrecht, Dessein, & Huylenbroeck, 2014). Many African governments have been slow to approve, or have sometimes even banned GM crops, in order not to lose export markets and to maintain positive relations with the EU, especially given implications for development aid

(Wafula, Waithaka, Komen, & Karembu, 2012). In addition, a few African nations have banned GM cultivation over fears of losing European markets (ISAAA, 2015). Public concerns over GM crops and foods have also had an impact on production of GM crops in North America. The withdrawal of the GM Bt potato (NewLeaf™) varieties from the North American market due to the concerns of two of the largest buyers of processing potatoes (Frito-Lay and McDonalds) was the result of feared consumer rejection (Kynda & Moeltner, 2006).

The extensive adaptation of GM crops does, however, also have some drawbacks. The occurrence of outcrossing with non-GM crops, gene flow, and the adventitious presence of GM crops on organic farms has sparked concerns among various stakeholders, including farmers who are growing GM crops (Ellstrand, 2003; Marvier & Van Acker, 2005). Public concern over GM crops is centered in three areas: human health, environmental safety, and trade impacts (Van Acker, Cici, Michael, Ryan, & Sachs, 2015). GM biosafety is also forcing both agriculture and food companies to appreciate GM safety in their marketing decisions (Blaine & Powell, 2001; Rotolo et al., 2015). The adoption of GM crops in a given jurisdiction is a function of public GM acceptance as well as the level of public trust of regulatory authorities (Vigani & Olper, 2013). Examples of these include feeding the world, consumer choice, and seed ownership (Van Acker & Cici, 2014). Opponents of GM crops have questioned their necessity in terms of agricultural productivity to feed the world (Gilbert, 2013). They point to studies that have shown that current agricultural output far exceeds global calorie needs and that distribution, access, and waste are the key limitations to feeding those who are hungry and not gross production *per se* (Altieri, 2005).

The novelty of GM technology has been both an asset and a challenge for those companies producing GM seeds. Supporters of GM crops have asserted that GM is merely an evolution of conventional breeding approaches (Herdt, 2006). They have insisted that humans have been genetically modifying crops for millennia and that GM technology has been an extension and facilitation of natural breeding. At the same time, however, GM crops are patentable, emphasizing that the process is truly novel and different from the natural breeding (Boucher, 1999). In addition, expert technical assessments acknowledge the unique and novel nature of GM crops (Taylor, 2007). This situation highlights the conundrum and challenge of not only introducing disruptive new technologies into society but having such technologies accepted by society (Van Acker et al., 2015). The socioeconomic nature of most risks along with the continuing farm income crisis in North America has led some to argue for the adoption of a more comprehensive approach to risk assessment of GM crops and all new agricultural technologies (Mauro et al., 2009).

The Green Revolution was driven by global hunger, and some argue that the next agricultural production revolution, which is perhaps being sparked by the introduction of GM crops, would be driven by other global needs including sustainability and the needs of individuals (Lipton & Longhurst, 2011). The green revolution of the 1960s and 1970s depended on the use of fertilizers, pesticides, and irrigation methods to initiate favorable conditions in which high yielding modern varieties could thrive. Between 1970 and 1990, fertilizer use in developing countries rose by 360% while pesticide use increased by 7 to 8% annually. The environmental impacts of the adoption of these technologies did in some cases override their benefits. These impacts included polluted land, water, and air, and the development of resistant strains of pests. GM crops could be used to sustain or grow production levels while diminishing environmental impacts yet despite the rapid adoption of GM crops many of the problems associated with the green revolution remain (Macnaghten & Carro-Ripalda, 2015). The pros and cons of GM crops are many and diverse but there is little argument over the ambiguous consequences of this comparatively new technology, and numerous critics noted the potential pros and cons of GM crops as soon as they were launched in the early 1990s (Mannion, 1995A, 1995B, 1995C).

Pros of GMO Crop Farming

The world population has exceeded 7 billion people and is forecasted to reach beyond 11 billion by 2100 (United Nations, 2017). The provision of an adequate food supply for this booming population is an ongoing and tremendous challenge. The companies that develop GM seeds point to this challenge as the key rationale for their need, and they explain that GM seeds will help to meet the “feeding the world” challenge in a number of ways

Productivity of GM Crops

GM seed companies promised to raise productivity and profitability levels for farmers around the world (Pinstrup-Andersen, 1999). GM seed companies had expected GM crops to be adopted by farmers because the traits they were incorporating provided direct operational benefits for farmers that could be linked to increased profits for farmers (Hatfield et al., 2014). The proponents of GM crops have argued that the application of GM technology would fundamentally improve the efficiency, resiliency, and profitability of farming (Apel, 2010). In addition GM seed companies argue that the adoption of GM crops helps to reduce the application of pesticides, which has a direct impact on the sustainability of the cropping systems (Lal, 2004) as well as profitability for farmers (Morse, Mannion, & Evans, 2011). Some have even suggested that the production of GM crops creates a halo effect for nearby non-GM crops by reducing pest pressures within regions that are primarily sown to GM crops (Mannion & Morse, 2013).

There is an expectation widely held by those in agriculture that GM seeds increase yields, or at least protect yield potential. GM crops with resistance to insects and herbicides can substantially simplify crop management and reduce crop losses, leading to increased yields (Pray, Jikun Huang, Hu, & Rozelle, 2002; Pray, Nagarajan, Huang, Hu, & Ramaswami, 2011; Nickson, 2005). GM varieties of soybean, cotton, and maize produced 20%, 15%, and 7% higher yield, respectively, than non-GM varieties (Mannion & Morse, 2013). The Economic Research Service (ERS) of the United States Department of Agriculture (USDA) noticed a significant relationship between increased crop yields and increased adoption of herbicide- and pesticide-tolerant GM crop seeds, and the USDA reported significantly increased yields when farmers adopted herbicide-tolerant cotton and Bt cotton

(USDA, 2009). India cultivated a record 11.6 million hectares of Bt cotton planted by 7.7 million small farmers in 2014, with an adoption rate of 95%, up from 11.0 million hectares in 2013. The increase from 50,000 hectares in 2002 to 11.6 million hectares in 2014 represents an unprecedented 230-fold increase in 13 years (James, 2014). This rapid adoption has been attributed to the increased yields farmers in this region experienced because of the efficacy of the GM seeds on cotton bollworm and the additional income farmers received as a result (James, 2014; Morse & Mannion, 2009). Similarly, the benefits that were obtained by resource-poor cotton farmers in South Africa have led many smallholders in South Africa and elsewhere in sub-Saharan Africa to accept GM cotton (Hillocks, 2009). Similar benefits were also obtained by resource-poor farmers growing Bt maize in the Philippines (James, 2010).

Tillage Systems

The adoption of no tillage and minimum tillage practices in agriculture started in the 1980s. In fact, the largest extension of both no tillage and conservation tillage and the concomitant declines in soil erosion significantly predates the release of the first HT varieties of maize and soybean in 1996 (National Research Council [NRC], 2010). However, farmers in the United States who adopted HT crops were more likely to practice conservation tillage and vice versa (NRC, 2010.) There was an increase in HT crops and conservation tillage in the United States during the period of rapid GM crop adoption from 1997–2002 (Fernandez-Cornejo, Hallahan, Nehring, Wechsler, & Grube, 2012). Soybeans genetically engineered with HT traits have been the most widely and rapidly adopted GM crop in the United States, followed by HT cotton. Adoption of HT soybeans increased from 17% of U.S. soybean acreage in 1997 to 68% in 2001 and 93% in 2010. Plantings of HT cotton expanded from about 10% of U.S. acreage in 1997 to 56% in 2001 and 78% in 2010 (Fernandez-Cornejo et al., 2012). Some argue that the adoption of GM HT varieties resulted in farmers' deciding to use conservation tillage, or farmers who were practicing conservation tillage may have adopted GM HT crops more readily (Mauro & McLachlan, 2008). Adoption of HT soybean has a positive and highly significant impact on the adoption of conservation tillage in the United States (Carpenter, 2010). Technologies that promote conservation tillage practices decrease soil erosion in the long term and fundamentally promote soil conservation (Montogomery, 2007), while reducing nutrient and carbon loss (Brookes & Barfoot, 2014; Giller, Witter, Corbeels, & Pablo, 2009; Mannion & Morse, 2013; Powlson et al., 2014). Adopting HT soybean has decreased the number of tillage operations between 25% and 58% in the United States and in Argentina (Carpenter, 2010). The introduction of HT soybean has been cited as an important factor in the rapid increase of no tillage practices in Argentina, and the adoption of no tillage practices in this region has allowed for wheat to be double cropped with soybean which has led to a fundamental increase in farm productivity (Trigo, Cap, Malach, & Villareal, 2009). Substantial growth in no tillage production linked to the adoption of GM HT crops has also been noted in Canada. Several authors have reported a positive correlation between the adoption of GM HT canola and the adoption of zero-tillage systems in western Canada (Phillips, 2003; Beckie et al., 2006; Kleter et al., 2007). The no tillage canola production area in western Canada increased from 0.8 million hectares to 2.6 million hectares from 1996 to 2005. This area covers about half the total canola area in Canada (Qaim & Traxler, 2005). In addition, tillage passes among farmers growing HT canola in Canada dropped by more than 70% in this same period (Smyth, Gusta, Belcher, Phillips, & Castle, 2011). Fields planted with HT crops in this region require less tillage between crops to manage weeds (Fawcett & Towery, 2003; Nickson, 2005).

Reductions in tillage and pesticide application have great benefits because they minimize inputs of fossil fuels in farming systems and in doing so, they reduce the carbon footprint of crop production (Baker, Ochsner, Venterea, & Griffis, 2007). The mitigation of soil erosion is important with respect to environmental conservation and the conservation of productivity potential. The adoption of no tillage practices would also save on the use of diesel fuel, and it enriches carbon sequestration in soils (Brookes & Barfoot, 2014). Brookes and Barfoot (2008) suggested that the fuel reduction because of GM crop cultivation resulted in a carbon dioxide emissions savings of 1215×10^6 Kg. This corresponds to taking more than 500,000 cars off the road. In addition, a further 13.5×10^9 Kg of carbon dioxide could be saved through carbon sequestration, which is equivalent to taking 6 million cars off the road. The impact of GM crops on the carbon flows in agriculture may be considered as a positive impact of GM crops on the environment (Knox et al., 2006).

Herbicide Tolerance and Pest Management

Herbicide tolerance (HT) in GM crops is achieved by the introduction of novel genes. The control of weeds by physical means or by using selective herbicides is time-consuming and expensive (Roller & Harlander, 1998). The most widely adopted HT crops are glyphosate tolerant (Dill, CaJabob, & Padgette, 2008) colloquially (and commercially for Monsanto) known as “Roundup Ready” crops. Herbicide tolerant GM crops have provided farmers with operational benefits. The main benefits associated with HT canola, for example, were easier and better weed control (Mauro & McLachlan, 2008). The development of GM HT canola varieties has also been linked to incremental gains in weed control and canola yield (Harker, Blackshaw, Kirkland, Derksen, & Wall, 2000). Despite all of the weed management options available in traditional canola, significant incentives remained for the development of HT canola. The most apparent incentives were special weed problems such as false cleavers (*Galium aparine*) and stork’s bill (*Erodium cicutarium*), and the lack of low-cost herbicide treatments for perennials such as quackgrass (*Agropyron repens*) and Canada thistle (*Cirsium arvense*). Mixtures of herbicides can control many of the common annual and perennial weeds in western Canada but they are expensive and not necessarily reliable (Blackshaw & Harker, 1992). In addition, some tank-mixtures led to significant canola injury and yield loss (Harker, Blackshaw, & Kirkland, 1995). Thus, canola producers welcomed the prospect of applying a single nonselective herbicide for all weed problems with little concern for specific weed spectrums, growth stages, tank mixture interactions (i.e., antagonism or crop injury) and/or extensive consultations. Two major GM HT canola options are widely used in western Canada. Canola tolerant to glufosinate was the first transgenic crop to be registered in Canada (Oelck et al., 1995). Canola tolerant to glyphosate (Roundup Ready) followed shortly thereafter. The GM HT canola offers the possibility of improved weed management in canola via a broader spectrum of weed control and/or greater efficacy on specific weeds (Harker et al., 2000). The greatest gains in yield attributed to the adoption of GM HT crops has been for soybean in the United States and Argentina and for GM HT canola in Canada (Brookes & Barfoot, 2008).

The reduction of pesticide applications is a major direct benefit of GM crop cultivation: reducing farmers' exposure to chemicals (Hossain et al., 2004; Huang, Hu, Rozelle, & Pray, 2005) and lowering pesticide residues in food and feed crops, while also releasing less chemicals into the environment and potentially increasing on-farm diversity in insects and pollinators (Nickson, 2005). Additionally, improved pest management can reduce the level of mycotoxins in food and feed crops (Wu, 2006). Insect resistance in GM crops has been conferred by transferring the gene for toxin creation from the bacterium *Bacillus thuringiensis* (Bt) into crops like maize. This toxin is naturally occurring in Bt and is presently used as a traditional insecticide in agriculture, including certified organic agriculture, and is considered safe to use on food and feed crops (Roh, Choi, Li, Jin, & Je, 2007). GM crops that produce this toxin have been shown to require little or no additional pesticide application even when pest pressure is high (Bawa & Anilakumar, 2013). As of the end of the 21st century, insect resistant GM crops were available via three systems (Bt variants). Monsanto and Dow Agrosciences have developed SmartStax maize, which has three pest management attributes, including protection against both above-ground and below-ground insect pests, and herbicide tolerance, which facilitates weed control (Monsanto, 2009). SmartStax maize GM varieties were first approved for release in the United States in 2009 and combine traits that were originally intended to be used individually in GM crops (Mannion & Morse, 2013). Significant reductions in pesticide use is reported by adoption of Bt maize in Canada, South Africa, and Spain, as well as Bt cotton, notably in China (Pemsl, Waibel, & Gutierrez, 2005), India (Qiam, 2003), Australia, and the United States (Mannion & Morse, 2013).

Human Health

GM crops may have a positive influence on human health by reducing exposure to insecticides (Brimner, Gallivan, & Stephenson, 2005; Knox, Vadakuttu, Gordon, Lardner, & Hicks, 2006) and by substantially altering herbicide use patterns toward glyphosate, which is considered to be a relatively benign herbicide in this respect (Munkvold, Hellmich, & Rice, 1999). However these claims are mostly based on assumption rather than real experimental data. There is generally a lack of public studies on the potential human health impacts of the consumption of food or feed derived from GM crops (Domingo, 2016; Wolt et al., 2010) and any public work that has been done to date has garnered skepticism and criticism, including, for example, the work by Seralini et al. (2013). However, the GM crops that are commercialized pass regulatory approval as being safe for human consumption by august competent authorities including the Food and Drug Administration in the United States and the European Food Safety Authority in Europe. Improvement of GM crops that will have a direct influence on health such as decreased allergens (Chu et al., 2008), superior levels of protein and carbohydrates (Newell-Mc-

Gloughlin, 2008), greater levels of essential amino acids, essential fatty acids, vitamins and minerals including, multivitamin corn (Naqvi et al., 2009; Zhu et al., 2008), and maximum zeaxanthin corn (Naqvi et al., 2011) hold much promise but have yet to be commercialized. Malnutrition is very common in developing countries where poor people rely heavily on a single food sources such as rice for their diet (Gómez-Galera et al., 2010). Nevertheless, rice does not contain sufficient quantities of all essential nutrients to prevent malnutrition and GM crops may offer means for supplying more nutritional benefits through single food sources such as rice (White & Broadley, 2009). This not only supports people to get the nutrition they require, but also plays a potential role in fighting malnutrition in developing nations (Sakakibara & Saito, 2006; Sauter, Poletti, Zhang, & Gruissem, 2006). Golden rice is one the most known examples of a bio-fortified GM crop (Potrykus, 2010). Vitamin A deficiency renders susceptibility to blindness and affects between 250,000 and 500,000 children annually and is very common in parts of Africa and Asia (Golden Rice Project, 2009). A crop like Golden rice could help to overcome the problem of vitamin A deficiency by at least 50% at moderate expense (Stein, Sachdev, & Qaim, 2008), yet its adoption has been hampered by activist campaigns (Potrykus, 2012).

Environmental Benefits

For currently commercialized GM crops the environmental benefits as previously pointed out are primarily linked to reductions in pesticide use and to reductions in tillage (Christou & Twyman, 2004; Wesseler, Scatasta, & El Hadji, 2011). Reductions in pesticide use can lead to a greater conservation of beneficial insects and help to protect other non-target species (Aktar, Sengupta, & Chowdhury, 2009). Reduced tillage helps to mitigate soil erosion and environmental pollution (Wesseler et al., 2011; Brookes & Barfoot, 2008) and can lead to indirect environmental benefits including reductions in water pollution via pesticide and fertilizer runoff (Christos & Ilias, 2011). It has been claimed that growing Bt maize could help to significantly reduce the use of chemical pesticides and lower the cost of production to some extent (Gewin, 2003). The deregulation process for GM crops includes the assessment of potential environmental risks including unintentional effects that could result from the insertion of the new gene (Prakash, Sonika, Ranjana, & Tiwary, 2011). Development of GM technology to introduce genes conferring tolerance to abiotic stresses such as drought or inundation, extremes of heat or cold, salinity, aluminum, and heavy metals are likely to enable marginal land to become more productive and may facilitate the remediation of polluted soils (Czako, Feng, He, Liang, & Marton, 2005; Uchida et al., 2005). The multiplication of GM crop varieties carrying such traits may increase farmers' capacities to cope with these and other environmental problems (Dunwell & Ford, 2005; Sexton & Zilberman, 2011). Therefore, GM technology may hold out further hope of increasing the productivity of agricultural land with even less environmental impact (Food and Agriculture Organization [FAO], 2004).

Some proponents of GM crops have argued that because they increase productivity they facilitate more sustainable farming practices and can lead to "greener" agriculture. Mannion and Morse (2013), for example, argue that GM crops require less energy investment in farming because the reduced application of insecticide lowers energy input levels, thereby reducing the carbon footprint. It has been suggested by other authors that the adoption of GM crops may have the potential to reduce inputs such as chemical fertilizers and pesticides (Bennett, Ismael, Morse, & Shankar, 2004; Bennett, Phipps, Strange, & Grey, 2004). Others note that higher crop yields facilitated by GM crops could offset greenhouse gas emissions at scales similar to those attributed to wind and solar energy (Wise et al., 2009). Greenhouse gas emissions from intensive agriculture are also offset by the conservation of non-farmed lands. While untilled forest soils and savannas, for example, act as carbon stores, farmed land is often a carbon source (Burney, Davis, & Lobell, 2010).

The Economy

GM crops are sold into a market and are subject to the market in terms of providing a realized value proposition for farmers and value through the food chain in terms of reduced costs of production (Lucht, 2015). Currently the GM crops on the market are targeted to farmers and have a value proposition based on economic benefits to farmers via operational benefits (Mauro, McLachlan, & Van Acker, 2009). Due to higher yield and lower production cost of GM crops, farmers will get more economic return and produce more food at affordable prices, which can potentially provide benefits to consumers including the poor (Lucht, 2015; Lemaux, 2009). The most significant economic benefits attributed to GM crop cultivation have been higher gross margins due to lower costs of pest management for farmers (Klümper & Qaim, 2014; Qaim, 2010). GM varieties have provided a financial benefit for many farmers (Andreasen, 2014). In some regions, GM crops have led to reduced labor costs for farmers (Bennett et al., 2005). Whether GM crops have helped to better feed the poor and alleviate global poverty is not yet proven (Yuan et al., 2011).

Cons of GMO Crop Farming

The intensive cultivation of GM crops has raised a wide range of concerns with respect to food safety, environmental effects and socioeconomic issues. The major cons are explored for cross-pollination, pest resistance, human health, the environment, the economy, and productivity.

Cross-Pollination

The out crossing of GM crops to non-GM crops or related wild type species and the adventitious mixing of GM and non-GM crops has led to a variety of issues. Because of the asynchrony of the deregulation of GM crops around the world, the unintended presence of GM crops in food and feed trade channels can cause serious trade and economic issues. One example is “LibertyLink” rice, a GM variety of rice developed by Bayer Crop Science, traces of which were found in commercial food streams even before it was deregulated for production in the United States. The economic impact on U.S. rice farmers and millers when rice exports from the United States were halted amounted to hundreds of millions of dollars (Bloomberg News, 2011). A more recent example is Agrisure Viptera corn, which was approved for cultivation in the United States in 2009 but had not yet been deregulated in China. Exports of U.S. corn to China contained levels of Viptera corn, and China closed its borders to U.S. corn imports for a period. The National Grain and Feed Association (NGFA) had encouraged Syngenta to stop selling Viptera because of losses U.S. farmers were facing, and there is an ongoing class-action lawsuit in the United States against Syngenta (U.S. District Court, 2017). Concerns over the safety of GM food have played a role in decisions by Chinese officials to move away from GM production. Cross-pollination can result in difficulty in maintaining the GM-free status of organic crops and threaten markets for organic farmers (Ellstrand, Prentice, & Hancock, 1999; Van Acker, McLean, & Martin, 2007). The EU has adopted a GM and non-GM crop coexistence directive that has allowed nation-states to enact coexistence legislation that aims to mitigate economic issues related to adventitious presence of GM crops in non-GM crops (Van Acker et al., 2007).

GM crops have also been criticized for promoting the development of pesticide resistant pests (Dale, Clarke, & Fontes, 2002). The development of resistant pests is most due to the overuse of a limited range of pesticides and overreliance on one pesticide. This would be especially true for glyphosate because prior to the development of Roundup Ready crops glyphosate use was very limited and since the advent of Roundup Ready crops there has been an explosion of glyphosate-resistant weed species (Owen, 2009). The development of resistant pests via cross-pollination to wild types (weeds) is often cited as a major issue (Friedrich & Kassam, 2012) but it is much less of a concern because it is very unlikely (Owen et al., 2011; Ellstrand, 2003). There are, however, issues when genes transfer from GM to non-GM crops creating unexpected herbicide resistant volunteer crops, which can create challenges and costs for farmers (Van Acker, Brule-Babel, & Friesen, 2004; Owen, 2008; Mallory-Smith & Zapiola, 2008).

Some critics of GM crops express concerns about how certain GM traits may provide substantive advantages to wild type species if the traits are successfully transferred to these wild types. This is not the case for GM HT traits, which would offer no advantage in non-cropped areas where the herbicides are not used, but could be an issue for traits such as drought tolerance (Buiatti, Christou, & Pastore, 2013). This situation would be detrimental because the GM crops would grow faster and reproduce more often, allowing them to become invasive (FAO, 2015). This has sometime been referred to as genetic pollution (Reichman et al., 2006). There are also some concerns that insects may develop resistance to the pesticides after ingesting GM pollen (Christou, Capell, Kohli, Gatehouse, & Gatehouse, 2006). The potential impact of genetic pollution of this type is unclear but could have dramatic effects on the ecosystem (Stewart et al., 2003).

Pest Resistance

Repeated use of a single pesticide over time leads to the development of resistance in populations of the target species. The extensive use of a limited number of pesticides facilitated by GM crops does accelerate the evolution of resistant pest populations (Bawa &

Anilakumar, 2013). Resistance evolution is a function of selection pressure from use of the pesticide and as such it is not directly a function of GM HT crops for example, but GM HT crops have accelerated the development of glyphosate resistant weeds because they have promoted a tremendous increase in the use of glyphosate (Owen, 2009). Farmers have had to adjust to this new problem and in some cases this had added costs for farmers (Mauro, McLachlan, & Van Acker, 2009; Mannion & Morse, 2013). The management of GM HT volunteers has also produced challenges for some farmers. These are not resistant weeds as they are not wild type species, but for farmers they are herbicide resistant weeds in an operational sense (Knispel, McLachlan, & Van Acker, 2008; Liu et al., 2015). Pink bollworm has become resistant to the first generation GM Bt cotton in India (Bagla, 2010). Similar pest resistance was also later identified in Australia, China, Spain, and the United States (Tabashnik et al., 2013). In 2012, army worms were found resistant to Dupont-Dow's Bt corn in Florida (Kaskey, 2012), and the European corn borer is also capable of developing resistance to Bt maize (Christou et al., 2006).

Human Health

Although the deregulation of GM crops includes extensive assessments of possible human health impacts by competent authorities there are still many who hold concerns about the potential risks to human health of GM crops. For some this is related to whether transgenesis itself causes unintended consequences (Domingo, 2016), while for others it is concerns around the traits that are possible using GM (Herman, 2003). Some criticize the use of antibiotic resistance as markers in the transgenesis procedure and that this can facilitate antibiotic resistance development in pathogens that are a threat to human health (Key, Ma, & Drake, 2008). Many critics of GM crops express concerns about allergenicity (Lehrer & Bannon, 2005). Genetic modification often adds or mixes proteins that were not native to the original plant, which might cause new allergic reactions in the human body (Lehrer & Bannon, 2005). Gene transfer from GM foods to cells of the body or to bacteria in the gastrointestinal tract would cause concern if the transferred genetic material unfavorably influences human health, but the probability of this occurring is remote. Other concerns include the possibility of GM crops somehow inducing mutations in human genes (Ezeonu, Tagbo, Anike, Oje, & Onwurah, 2012) or other unintended consequences (Yanagisawa, 2004; Lemaux, 2009; Gay & Gillespie, 2005; Wesseler, Scatasta, & El Hadji, 2011) but commentary by these authors is speculative and is not based on experimentation with current GM crops.

Environment

For currently commercialized GM crops the potential environmental impacts are mostly related to how these crops impact farming systems. Some argue that because crops like Roundup Ready soybean greatly simplify weed management they facilitate simple farming systems including monocultures (Dunwell & Ford, 2005). The negative impact of monocultures on the environment is well documented and so this might be considered an indirect environmental effect of GM crops (Nazarko, Van Acker, & Entz, 2005; Buiatti, Christou, & Pastore, 2013). Other concerns that have been raised regarding GM crops include the effects of transgenic on the natural landscape, significance of gene flow, impact on non-target organisms, progression of pest resistance, and impacts on biodiversity (Prakash et al., 2011). Again, many of these concerns may be more a function of the impacts of simple and broad-scale farming practices facilitated by GM crops rather than GM crops per se. However, there has been considerable concern over the environmental impact of Bt GM crops highlighted by studies that showed the potential impact on monarch butterfly populations (Dively et al., 2004). This begged questions then about what other broader effects there may be on nontarget organisms both direct and indirect (Daniell, 2002). In addition, there may be indirect effects associated with how GM crops facilitate the evolution of pesticide resistant pests in that the follow-on control of these pest populations may require the use of more pesticides and often older chemistries that may be more toxic to the environment in the end (Nazarko et al., 2005).

The Economy

Bringing a GM crop to market can be both expensive and time consuming, and agricultural bio-technology companies can only develop products that will provide a return on their investment (Ramaswami, Pray, & Lalitha, 2012). For these companies, patent infringement is a big issue. The price of GM seeds is high and it may not be affordable to small farmers (Ramaswami et al., 2012; Qaim, 2009). A considerable range of problems has been associated with GM crops, including debt and increased dependence on multinational seed companies, but these can also be combined with other agricultural technologies to some extent (Kloppenburg, 1990; Finger et al., 2011). The majority of seed sales for the world's major crops are controlled by a few seed companies. The issues of private industry control and their intellectual property rights over seeds have been considered problematic for many farmers and in particular small farmers and vulnerable farmers (Fischer, Ekener-Petersen, Rydhmer, & Edvardsson Björnberg, 2015; Mosher & Hurburgh, 2010). In addition, efforts by GM seed companies to protect their patented seeds through court actions have created financial and social challenges for many farmers (Marvier & Van Acker, 2005; Semal, 2007). There is considerable debate about the extent to which GM crops bring additional value to small and vulnerable farmers with strong opinions on both sides (Park, McFarlane, Phipps, & Ceddia, 2011; Brookes & Barfoot, 2010; James, 2010; Smale et al., 2009; Subramanian & Qaim, 2010). As the reliance on GM seeds extends, concerns grow about control over the food supply via seed ownership and the impacts on the diversity of seed sources, which can impact the resilience of farming systems across a region (Key et al., 2008). The risk of GM crops to the world economy can be significant. Global food production is dominated by a few seed companies, and they have increased the dependence of developing countries on industrialized nations (Van Acker, Cici, Michael, Ryan, & Sachs, 2015).

Productivity

Justification for GM crops on the basis of the need to feed the world is often used by proponents of the technology, but the connection between GM crops and feeding the world is not direct. GM crops are used by farmers and are sold primarily on the basis of their direct operational benefits to farmers, including the facilitation of production and/or more production (Mauro et al., 2009). Farmers realize these benefits in terms of cost savings or increased production or both and are looking to increase their margins by using the technology. Companies producing GM seeds can be very successful if they are able to capture a greater share of a seed market because they supply farmers with operational benefits such as simplified weed management (Blackshaw & Harker, 1992) even if there are no productivity gains. In addition, the traits in GM crops on the market as of the early part of the 21st century are not yield traits per se but are yield potential protection traits that may or may not result in greater productivity.

Conclusions

Genetic modification via recombinant DNA technology is compelling because it does provide a means for bringing truly novel traits into crops and the adoption of GM crops has been rapid in a range of countries around the world. Only a very limited number of traits have been incorporated to date into GM crops, the two primary traits being herbicide tolerance (HT) and insect resistance. Nonetheless, farmers who have adopted GM crops have benefited from the operational benefits they provide, and current GM crops have facilitated the adoption of more sustainable farming practices, in particular, reduced tillage. The ongoing asynchronous approvals of GM crops around the world mean that there will always be issues related to the adventitious presence of GM crops in crop shipments and trade disruptions. Pollen mediated gene flow from crop to crop and seed admixtures are challenges of GM crop farming and agricultural marketing as a result. The adoption of GM HT crops has also accelerated the evolution of herbicide resistant weeds, which has created additional operational challenges and costs for farmers. The GM crops commercialized to date have all been deregulated and deemed to be safe to the environment and safe in terms of human health by competent authorities around the world, including the European Food Safety Association. There remain, however, critics of the technology who point to a lack of public research on the potential risks of GM and GM crops. GM crops will continue to be developed because they provide real operational benefits for farmers, who are the ones who purchase the seeds. The novelty of the technology and its potential to bring almost any trait into crops mean that there needs to remain dedicated diligence on the part of regulators to ensure that no GM crops are deregulated that may in fact pose risks to human health or the environment, but there will also remain the promise of the value of novel inventions that bring benefits to consumers and the environment. The same will be true for the next wave of new breeding technologies, which include gene editing technologies such as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) (Cong et al., 2013). These new technologies have even greater potential for modifying crops than GM technology and they avoid some of the characteristics of GM technology that have underpinned criticisms including, for example, the presence of foreign DNA.

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