The New Zealand Institute of Agricultural & Horticultural Science Inc

Hot Topic #6 Real or imagined – Intended and unintended consequences of genetically modified crops

John Caradus

John Caradus, Grasslanz Technology Ltd,
PB 11008, Palmerston North 4442, New Zealand
Email: john.caradus@grasslanz.com
ORCID number: John Caradus 0000-0001-7887-9041

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The following link is to a discussion on gene editing and GM technologies and the choice facing New Zealand in how these opportunities should be regulated so that benefits and risk can be balanced for improved environmental and economic outcomes.
https://www.fieldays.co.nz/from-the-field/fieldays-tv-on-demand?video=vod-2022-gene-editing-the-pros-cons

Introduction

'Genetic modification' resulting in altered DNA sequences, is an overarching term that covers several different methods used in manipulating the genome of organisms. It does not refer to 'breeding' or 'mutagenesis', which can also modify DNA sequences. The genetic modifications may include transgenic manipulations, gene stacking, gene silencing and engineered changes to gene expression, and targeted editing that can result in the deletion, modification and insertion of genetic material (Arujanan and Aldemita 2015; Mall et al. 2018; El-Mounadi et al. 2020).

Food and feed have been produced from genetically modified (GM) crops for 25 years, and it is timely to review whether this technology has delivered global benefits and whether ongoing debate about 'risk' is justified.

The 'Biosafety Clearing House' (see https://bch.cbd.int/en/); an online platform for facilitating the implementation of the Cartagena Protocol on Biosafety (see https://bch.cbd.int/protocol/), records 913 'living modified organisms' developed for resistance to diseases and pests, resistance to herbicides and antibiotics, tolerance to abiotic stresses, changes in physiology and or production, changes in quality and/or metabolite content, production of medical or pharmaceutical compounds, use in industrial applications, and for an engineered gene drive application (Convention on Biological Diversity 2022). It has been suggested that a significant driver for the implementation of these GM technologies is the "genetic glass ceiling", where the genes available for desired traits are not available within a given species, and hence cannot be captured by classical breeding approaches (Gressel 2010).

It is perhaps then unsurprising that genetically modified (GM) food and feed crops have been adopted at a faster rate than any other recent crop technology (Prabha et al. 2020; Scheitrum et al. 2020). There have been 525 different transgenic events undertaken in 32 crops and flower species that have been approved for cultivation in different parts of the world (Kumar et al. 2020; Verma et al. 2022) and they are used on 192 million hectares of land (ISAAA 2018a). Between 1992 and 2018, regulatory agencies across 43 countries (with the European Union counted as one country), and including New Zealand, have approved 2063 GM foods and 1,461 GM feeds for use, with them being considered as safe as non-GM crops (ISAAA 2018b). This is underpinned by 824 approvals allowing the cultivation of GM crops for eight types of GM traits (ISAAA 2022). The main commercialised GM crops are those providing glyphosate tolerance to improve weed control (Green and Owen 2011;

ISAAA 2017) and those incorporating genes expressing insecticidal proteins from Bacillus thuringiensis (Bt) (Duke and Powles 2009; Barrows et al. 2014a).

Currently, GM crops are grown in 26 countries (ISAAA 2018a) with the top five (ranked by area grown) being USA, Brazil, Argentina (Mühl 2020), India, and Canada (Kamle et al. 2017). In 2018, 21 developing countries grew 54% of the global GM crops by area (ISAAA 2018a), and a total of 70 countries (26 allowing planting and 44 not allowing planting of GM crops) adopted 30 GM crops for food, feed, and cultivation (ISAAA 2018b). The range of plant species grown as commercial GM crops is diverse including row crops, vegetables, and fruit trees (Parisi et al. 2016) but the predominant crops are maize (Zea mays), soybean (Glycine max), cotton (Gossypium hirsutum), and canola (Brassica napus) (James 2016; ISAAA 2018a), many of which have multiple 'stacked' traits (Parisi et al. 2016; Shehryar et al. 2020).

Despite this uptake, there is still debate about the balance of benefits and risks associated with this technology (Kumar et al. 2020; Kavi Kishor et al. 2021). This is often politically motivated, and political interference has substantially impacted regulatory approval processes for GM crops. This is considered to have adversely affected the adoption of innovative, yield enhancing crop varieties, thereby limiting food security opportunities in food insecure economies (Raybould 2021; Smyth et al. 2021).

Genetically modified crops – expected benefits from the new/modified traits

Economic gains

For the 22-year period to 2018 the global net economic benefit at the farm level of using GM crops has been calculated to be close to US$225 billion, with these gains almost equally accruing to farmers in developed and developing countries (Brookes and Barfoot 2020b). Interestingly, early in the commercial development of GM crops, the likely economic benefit of glyphosate tolerant soybean in USA was examined. It was suggested that the price premium for a GM variety was being set too high relative to the potential cost/risk savings on many farms, and as a result 'Roundup Ready soybean will not be fully adopted soon' (Bullock and Nitsi 2001). How wrong that prediction has proven, with glyphosate-tolerant GM soybean being the most cultivated transgenic plant in the world by 2006, and in the USA, making up 91% of soybean crop in 2007 (Bonny 2008), with an estimated cumulative global benefit over 15 years to 2010 of US$46 billion (Alston et al. 2014).

Improved productivity and crop yield performance

It has been estimated that GM crop production globally has increased by a cumulative 658 million tons compared with non-GM equivalents over the 20 years from 1996 to 2016 and in so doing has reduced the area requiring to be cropped by 183 million ha (ISAAA 2018b). What-is-more, the yields of GM crops of soybean, maize, canola, and cotton have increased globally since 1996 compared with equivalent non-GM crops (Brookes and Barfoot 2017). Using aggregate results from across-country time-series data, GM crops have been estimated to have increased yields by 34 per cent for cotton, 12 per cent for maize and 3 per cent for soybeans (Barrows et al. 2014b). Benefits from GM crops, especially in terms of increased yields, are greatest for the mostly small farmers in developing countries. They have benefitted from the spill-over of technologies that were originally targeted at farmers in industrialised countries (Huang et al. 2002b; Bennett et al. 2006; Carpenter 2010).

Crop management

The use of herbicide tolerant GM crops has been to the primary benefit of farmers and has provided an option for improved ease of management (Marra et al. 2004; Bonny 2011; Green and Owen 2011). It has been argued that with 95% of the USA soybean market dominated by GM cultivars, this reflects the ease of use to the US farmer. For example, growing herbicide tolerant GM soybean enables use of a no-till management system, leading to reduced energy inputs and a significant reduction in the use of chemical inputs for farming the soybean crop (down by 27,000 tonnes per year) (Livermore and Turner 2009).

Crop product composition and quality

For many years after the first commercial GM crops were grown and harvested, the compositional equivalency between GM and non-GM crops has been at the heart of human health safety assessments. A substantial literature review in 2013 concluded that unintended compositional effects that could be caused by genetic modification had not materialised (Herman and Price 2013). Additionally, a meta-analysis of 32 publications, over 21 years of field trials, has revealed that GM maize cultivation led to a significant increase in yield but no difference in the concentration of proteins, lipids, acid detergent fibre, neutral detergent fibre and total dietary fibre in grain compared with genetic isolines or near isolines (Pellegrino et al. 2018). What-is-more, one substantial and unintended benefit of Bt GM maize (single stacked Cry1Ab hybrids) was the lower concentrations of grain mycotoxins, such as fumonisins and thricotecens compared with non-GM maize (Ostry et al. 2010). This has been valued as worth about US$23 million annually in the USA (Wu 2006).

Agronomic and phenotypic plant traits

A field trial, undertaken by Bayer Crop Science in Brazil, comparing single or stacked GM materials, and non-GM counterparts as controls, and over six sites, has suggested that combining various GM events using conventional breeding approaches, does not alter the agronomic or phenotypic characteristics of soybean (7 events), maize (6 events) and cotton (6 events) crops compared to non-GM equivalents (Jose et al. 2020). Similarly, field trials by Dow AgroSciences also revealed no agronomic differences between maize hybrids developed through stacking of four individual transgenic events containing the cry1A.105 and cry2Ab2 (MON 89034), cry1F and pat (TC1507), cp4 epsps (5-enolpyruvylshikimate-3-phosphate synthase) and aad-1 transgenes, and non-GM near-isogenic hybrids (de Cerqueira et al. 2017).

Increased resistance to pests

Increasing resistance to major and minor pests of most crops has been a key goal for plant breeders. However, there are limits to how successful that strategy can continue to be using conventional breeding approaches, given changing pest populations and increased agricultural intensification that has been driven by economic and environmental (further encroachment into natural ecosystems) needs. The advent in 1996 of Bt GM plants expressing pesticidal proteins has provided an opportunity to enhance plant resistance as part of integrated pest management strategies (Hillocks 2014; Machado et al. 2020). A principal advantage of Bt insecticides is that they are generally not harmful to humans, and non-targeted to wildlife or beneficial arthropods (Ortman et al. 2001).

Environmental benefits

The application of professionally managed GM crops has led to improved environmental sustainability (Sharma et al. 2022) due to a reduction in use of synthetic chemicals, less soil disturbance, and with higher productivity there is a reduced need for more land to be claimed for agricultural production.

Reduced use of synthetic chemicals

While synthetic pesticides have been required to ensure economic crop yields (Pimentel 2005), they have also resulted in some concerning ecological consequences. These include potentially affecting non-target species, and possibly contaminating the food sources of other organisms (Devine and Furlong 2007), and waterways (Rosic et al. 2020; Rasool et al. 2022). There is reliable evidence of reduced pesticide use associated with the growing Bt GM crops (Lu et al. 2012; Klümper and Qaim 2014; Gruissem 2015; Nalluri and Karri 2020). Yield gains and pesticide reductions are larger for insect-resistant crops than for herbicide-tolerant crops, and yield and profit gains are higher in developing countries, than in developed countries.

Lower carbon footprint and reduced greenhouse gas emissions

The use of GM crops has been revealed to reduce the carbon footprint of cropping. It reduces the use of petrochemicals because of fewer herbicide and pesticide applications, and it reduces the need from soil cultivation and/or enables the use of no-till or reduced-till practices that allow carbon to remain in the soil (Brookes and Barfoot 2020c). Brookes and Barfoot (2020c) have estimated that 34 million tons of CO2 was not released from the reduced fuel use associated with growing GM crops.

Reduced tillage

Reduced tillage has been considered to have positive effects on the soil microbiome and soil structure (Frisvold et al. 2009; Fernandez-Cornejo et al. 2012), but that is not universally accepted (Janušauskaite et al. 2013; Schlüter et al. 2018). Despite these divergent views, one benefit that has been heralded for using GM crops is the reduction in tillage used in non-GM crops for managing weed incursion (Marra et al 2004). This results in maintained levels of sequestered soil carbon (Lee et al. 2014; Hussain et al. 2021) particularly in the surface layers (Deen and Kataki 2003; Brown et al. 2021).

GM product quality and safety testing for consumption by either animals or humans

Providing confidence on the safety of derived food for human consumption and feed for animals is paramount for any technology to be trusted and accepted. Indeed, the consumption of any modified or new foods, either by animals or humans, needs to be effectively and thoroughly tested for their impact on health and welfare. It has been argued that food from GM crops may be safer than food derived from non-GM crops, largely because the risks associated with GM crops are readily quantified and monitored as part of the rigorous assessment system that goes beyond that applied to non-GM derived foods (Halford and Shewry 2000).

GM feed for animals

Most output from GM crops is used in animal feed rather than human food. An estimated 70 to 90% of all GM crops, principally soybean and maize, but also including cotton and canola, are used to feed animals (Flachowsky et al. 2012; Ritchie and Roser 2021) with the biggest users being USA, China, and Europe (Baulcombe et al. 2014). The general conclusion is that most GM crops used for animal feed have input traits that do not change their composition or nutritional value for these animals, and that feeding GM crops does not result in detection of transgenic DNA or their translated proteins in the meat, milk, or eggs derived from the animals (Akram et al. 2019; Blair and Regenstein 2020).

Food safety for human consumption

The advent of GM crops has led to concerns about food safety and the need for rigorous testing (Nordic Working Group 1991; OECD 1993, 1998; Pusztai 2001, 2002). To manage potential risks from using GM crops there has nearly always been a framework of science-based risk assessment and risk management measures in place to oversee their commercialisation (Craig et al. 2008). The generally accepted conclusion is that there has been no evidence of ill effects linked to the consumption of any approved GM crop (The Royal Society 2016; Ladics 2019). There is no doubt that testing for potential health effects of GM crops is complex and polarising. The situation is well described by DeFrancisco (2013) who concludes that 'critics and proponents of GM crops alike agree that genetically modified foods have failed to produce any untoward [human] health effects, and that the risk to human health from foods contaminated with pathogens is far greater than from GM crops'. Indeed, extensive reviews of the impacts of GM crops such as Bt corn, cotton and maize, conclude that they are nontoxic to humans and pose no significant concern for allergenicity (Betz et al. 2000; Sasson 2018).

Food quality and nutritive value

Two issues need to be examined here: (1) the deliberate use of GM technologies to improve the nutritional value of crops, and (2) the impact of transgenes introduced to provide other traits on a crop's nutritional quality. For many years, it has been considered that crops could be genetically transformed to improve their nutritive quality and value to eradicate or lessen the impact of malnutrition in some countries (Bouis 2007; Farre et al. 2011; Garg et al. 2018). Attitudes towards the use of biofortified foods (produced using supplementation rather than GM technologies), has also led to a struggle for them to be adopted without approved health and nutrition claims (Gannon et al. 2104; Wortmann et al. 2018; Welk et al. 2021).

In seeking to understand the extent of unintended effects of transgenes on composition and nutritional value, the compositional analyses of 129 GM crops have been investigated by the US Food and Drug Administration. They revealed no significant differences for any plant compounds believed to have biological relevance when these GM crops were compared to non-GM equivalents (DeFrancesco 2013).

Unintended consequences of traits in GM crops – fact or myth?

While many people have condemned GM crops for suspected 'unintended consequences', some of these claims need better scrutiny, while others need to be taken seriously and managed appropriately. Indeed, if one reflects on non-GM conventional agricultural methods, there is no doubt that herbicide and pesticide application can have large and well-documented unintended consequences. While 'two wrongs don't make a right' it is worth examining whether the use of GM crops may result in fewer, less concerning, and more easily managed unintended consequences.

Does GM increase the herbicide tolerance of weeds?

Herbicide resistance in weeds is a global issue and not just restricted to, or solely caused by, the use of herbicide tolerant GM crops (Heap 2014). In 2022, there were 56 weeds recognised as exhibiting resistance to glyphosate worldwide, although several are not associated with glyphosate tolerant GM crops (Weedscience 2022). Where herbicide tolerance of weeds has developed in GM crops (Ghanizadeh et al. 2019; Rigon et al. 2020) the issue appears to be more to do with the poor management and the inappropriate use of the herbicides, not the development of the GM crops per se.

Overuse of pesticides

There have been instances where economically important pests have become resistant to synthetic insecticides. This can lead to overuse of insecticides in a desperate bid to control the pest (Benbrook 2012). However, this situation can also be resolved using Bt GM crops. A good example of this occurred in China, where cotton bollworm (Helicoverpa armigera) became resistant to the pesticides being used in the 1990s and ongoing control came from the use of Bt cotton in the late 1990s (Wu et al. 2008; Lu et al. 2010).

Secondary pests becoming dominant

Despite the proposition that the use of glyphosate tolerant GM crops would reduce (or at least not increase) total herbicide use (Gianessi 2005; Bonny 2008), there is an alternative proposition (Benbrook 2012). The argument is that while GM Bt crops may reduce targeted insect pests, they provide an opportunity for secondary pests to prevail (Zhao et al. 2011). Indeed, it has been shown in USA that Bt GM maize expressing Cry1Ab protein, which controls the European maize borer and maize earworm (Helicoverpa zea), provides a competitive advantage to another pest, the western bean cutworm (Striacosta albicosta), particularly when maize earworm numbers and fitness were reduced (Dorhout and Rice 2010). Experience with Bt cotton has revealed that the emergence of secondary pests requires adjustments to pest management systems to address the emergence of the 'new' pests (Kennedy 2008).

Impacts on non-target organisms

The GM crop traits are primarily targeted to control a specific pest or pathogen (Rahman et al. 2015), whereas crop protection chemicals may affect beneficial organisms as well as the intended target (Cattaneo et al. 2006). A meta-analysis of 10 publications on Bt GM maize plants expressing resistance to Coleoptera (35%) and Lepidoptera (65%) has shown that GM maize cultivation has no effect on most non-target organism in a range of taxonomic groups (Pellegrino et al. 2018). It appears that most of the concerns about impacts from GM crops on non-target organism, mostly arthropods, are found in laboratory or controlled feeding studies, but rarely in the trial observations.

Resistant insect populations

Many pests have developed resistance to specific synthetic chemical pesticides (Devine and Furlong 2007; Maino et al. 2018; Hawkins et al. 2019). While there are about 70 types of Cry genes associated with proteins from B. thuringiensis, only a few are used in commercial GM crops (Sanchis 2011; Mehboob-ur-Rahman 2015). It was noted that after the first eight years of use of Bt crops, and despite dire warnings; pest resistance to Bt crops had yet to be documented (Bates et al. 2005). However, field resistance to the proteins produced by the Bt Cry genes has since then been observed (Pandian and Ramesh 2020) and has led to the need to develop insect resistance management processes (Kebebe 2020), involving the use of refuges alongside GM crops (Huang et al. 2011; Van den Berg et al. 2013). This strategy ensures that a specified proportion of the crop is planted to a non-Bt variety of the crop to serve as a refuge hosting susceptible insects. Another viable option involves the stacking or pyramiding of Bt genes (Storer et al. 2012; Van den Berg et al. 2013; Bacalhau et al. 2020), such that the acquisition of resistance required multiple different genetic changes to occur in the pest .

Increased weediness

The development of GM crops has been criticised for potentially increasing the weediness or invasiveness of the modified plants (Pilson and Prendeville 2004), although this has not been observed. But it has been observed that. GM arable crops are unlikely to survive for long outside cultivation (Crawley et al. 2001), this likely reflecting either their suboptimal survival outside of agronomic uses and/or the cost of prior conventional breeding that has selected for beneficial agronomic and production traits, that are a net cost to the plant.

Impacts on biodiversity

It has been stated that "favouring biodiversity does not exclude any future biotechnological contributions, but favouring biotechnology threatens future biodiversity resources" (Jacobsen et al. 2013). These authors proposed that research should be focused on areas of plant science, e.g., nutrition, policy research, governance, and solutions close to local market conditions, if the goal is to provide sufficient food for the world's growing population in a sustainable way. Maintenance of biodiversity has been promoted as a necessary requirement for beneficial ecological outcomes (Tilman et al. 2014; Schütte et al. 2017). There is no doubt that preservation of biodiversity in natural ecosystems is of paramount importance, however there is still debate on whether biodiversity is beneficial, or even necessary in productive agricultural ecosystems. The use of GM crops per-se has been argued as a threat to biodiversity within crop species (Gepts and Papa 2003), but several studies have concluded that the use of GM crops has not significantly affected levels of genetic diversity within crop species (Bowman et al. 2003; Sneller 2003; Ammann 2005).

Transgene escape into wild or non-GM populations

Gene flow from GM crops into wild or weedy relatives has been viewed as a potential unintended consequence of their use (Lu and Snow 2005; Wilkinson and Ford 2007; Lu 2008; Ryffel 2014), with this resulting in their increased fitness through improved resistance to insects, diseases, herbicides, or harsh growing conditions (Snow 2002), or through the genetic erosion of commonly owned landraces (Garcia and Altieri 2005). For out-crossing species, such as brassica (Warwick et al. 2003; Ford et al. 2006) it is difficult, if not impossible, to prevent gene flow from GM cultivars to wild/weedy and non-GM plants of the same or related species. The question then to consider is whether the transfer of transgene would be detrimental and create an unmanageable risk? It has been concluded that while transgenes that confer resistance to pests and environmental stress and/or lead to greater seed production have the greatest likelihood of aiding weeds or harming non-target species (Légère 2005; James 2006) this is unlikely for most currently grown transgenic crops (Prakash et al. 2011).

Pollen drift from GM plants may be prevented by carefully maintaining crop-specific isolation distances and using border strips around fields to trap pollen, or by using molecular methods to reduce the viability of the pollen (Kim et al. 2020; Prabha et al. 2020). The selective advantage associated with a transgene in a GM crop is an important consideration, such that traits related to the success of gene flow, or resistance to biotic or abiotic stresses, may result in selective advantages or improved fitness (Ammann et al. 1994).

Impact on rhizosphere microorganisms

A review of the direct, indirect, and pleiotropic effects of GM plants on soil microbiota, revealed impacts that depend on the transformation events, experimental conditions and taxa analysed (Turrini et al. 2015). In an extensive review Mandal et al. (2020) concluded that while some studies suggest that GM crops caused considerable changes in the structure and functions of indigenous soil microbial community, interpreting the real impact of GM crops on soil microorganisms was often confounded by the soil heterogeneity, varying nutritional requirements of the crops and the lack of suitable controls in the experiments.

Horizontal gene flow

Horizontal or lateral gene transfer is the transfer of genetic material from one organism to another with reproduction or human intervention (Keeling and Palmer 2008; Keese 2008). Indeed, gene transfer processes between bacteria in the phytosphere may be part of their evolutionary development and adaptation to plant rhizospheres (van Elsas et al. 2003). However, it has been concluded that the frequency of horizontal gene transfer from plants to other eukaryotes or prokaryotes is extremely low, albeit to viruses it is potentially greater, but the impact is restricted by selection pressures. Keese (2008) in a thorough review concluded that horizontal gene transfer from GM plants poses negligible risks to human health or the environment.

Increased antibiotic resistance

If transgenes can move through horizontal gene transfer, then one concern would be the rise of antibiotic resistance. The production of GM plants sometimes uses a genetic construct which includes not only the gene of interest and the relevant promoter, but also an antibiotic-resistant gene, used as a selectable marker. Bennett et al. (2004b) concluded that the risk of transfer of antibiotic resistance genes from GM plants to bacteria is remote, and that the hazard arising from any such gene transfer, subsequent genome incorporation, and transmission to humans, is extremely remote (Gay and Gillespie 2005). After over 25 years of commercial use of GM crops there is no documented evidence of this having occurred.

Gene transfer to consumers from GM food and feed

In one study, the transfer of transgenic DNA from GM feed to the tissues of piglets was considered, and it was concluded that the risk of gene transfer from GM food is no different from gene transfer from DNA in non-GM feeds (Mazza et al. 2005). Another study of the potential for movement of the 5-enolpyruvylshikimate-3-phosphate synthase (epsp) gene (found in GM soybean) to humans suggested that while it might survive stomach digestion and pass through into the small intestine it was completely degraded in the large intestine and did not alter gastrointestinal function, nor pose a risk to human health (Netherwood et al. 2004).

Unintended compounds produced

The concern of either new or known toxins being produced by GM crops has been proposed (Kessler et al. 1992), but with very little evidence to justify the concern (Ladics et al. 2015). Conversely, it has been shown that Bt GM maize not only does not produce unexpected toxins, but that its use may reduce fumonisin, deoxynivalenol and zearalenone contamination (known mycotoxins) as a health benefit (Ostry et al. 2010). Reduced fungal infection and hence potential production of mycotoxins, has been demonstrated due to reduced damage from European maize borers (Munkvold et al. 1997, 1999).

Summary – balancing the risk and benefits

Despite all the warnings and fearmongering about the perils of using GM crops it has been concluded by many, that most of the risks associated with their use have proven to be low, to non-existent (Carzoli et al. 2018; Vega Rodríguez et al. 2022). Perhaps the most concerning issue is the possible development of GM induced insect resistance or plant herbicide resistance, but such resistance is not confined to GM crops, as resistance in target insects and weeds is also evident in non-GM crop production systems (Mannion and Morse 2013). Even though GM crops have been used for either animal feed or human food for over 25 years in the USA, there has been no legitimately recorded cases of health-related issues. All concerns linking health-related issues to GM feed fed to animals, and that have extrapolated the findings to suggest similar effects in humans, have come from laboratory trials, not from human testing or public health experiences. A recent review (Lynas et al 2022) has reported that misinformation – defined as information which is at variance with widely-accepted scientific consensus – on GM crops and food in the mainstream and online news media is a major concern. Over a two-year period the overall falsehood rate was 9% for a potential readership of 256 million and where none of the misinformation identified was positive in sentiment. They concluded that misinformation about GM crops and food in the mainstream media is a significant problem that even outranks the proportion of misinformation in other comparable debates such as COVID-19 and vaccines.

What-is-more, the prevailing negative commentary on GM crops must be countered by the provision of reliable, fact/data based and peer reviewed information, which spells out the benefits and how risks, if any, are managed for better outcomes for the environment, economy, and society (Cook et al. 2004; Gaskell et al. 2004; Nerlich et al. 2004; Tallapragada et al. 2020; Kubisz et al. 2021). Rational public debate and dialogue on the benefits and risks of GM crops is needed (Borch and Rasmussen 2002, 2005; de Bakker et al. 2016), and it needs to be devoid of political, business or lobby-group influence. These debates need to be open and fact-based.

Concluding commentary

GM crops are one successful means of improving on farm productivity and profitability, the environment, and they have consumer benefits. This does not exclude the use of other technology options for similar improvements. The practices and technologies used have led to increases in water use efficiency, improvements to soil health and fertility, and pest control with minimal or zero-pesticide use. The suggested antagonism between approaches that use agroecology or biotechnology to deliver sustainable agricultural production (Heinemann 2009) makes no sense, and the fact that many people consider them mutually exclusive defies logic and common-sense. Extensive reviewing of the impacts of GM crops has shown that:

1. They provide considerable benefits to farmers, consumers, and the environment;
2. The technologies, just like many non-GM technologies, can bring risks, but these can be monitored and quantified, and allow decisions to be made about commercial, societal, and environmental benefits, versus real risks;
3. GM technologies are a valuable option that need to be promoted to solve current food/feed challenges and as

a result improve not simply economic outcomes, but also the environment.

4. Evaluation of outputs from GM technologies needs to continue to be 'de-risked' before being made commercially available; and
5. While 'checks' and 'balances' are required, regulatory schemes need to focus on balancing risks and benefits, and not just on 'checks. This is the situation currently for many countries including New Zealand were the HSNO Act 1996 needs review to allow a less adversarial path to the establishment of regulated field trials for research using containment to manage any risk.

Globally GM crops provide food and feed, and they are arguably already the most highly regulated biological technology in the world (DeFrancesco 2013; Baulcombe et al. 2014). There is a considerable body of good science describing and analysing GM technologies and their consequences, whether intended or unintended, and this must be the foundation for ensuring good and workable regulation.

New Breeding Technologies (NBTs) (synonymous with the term New Genomic Techniques (NGTs) (Parisi and Rodríguez-Cerezo 2021)) continue to emerge and they differ from older forms of transgenesis and genetic engineering in terms of the precision and targeting of effects. The NBTs include gene editing, targeted changes to a small number of bases of DNA using oligonucleotide-directed mutagenesis, cisgenesis, intragenesis, and the use of epigenetic processes to change the activity of genes without changing the genes DNA sequence. Accordingly, one must ask whether these NBTs should be regulated differently?

Currently in many jurisdictions, including New Zealand and the EU, NBTs are subject to the same regulations governing the use of genetically modified organisms (Purnhagen and Wesseler 2020; Zimny and Eriksson 2020; Caradus 2022). A revision of policies regulating GM crops is required, reflecting that NBTs are becoming the preferred means for introducing new traits into crop and forage plants (Gould et al. 2022; Mbaya et al. 2022). Furthermore, the inclusion of NBT innovations, at the very least, into organic farming systems would be a sensible and pragmatic option (Purnhagen et al. 2021), especially given the production inefficiencies and increased energy/carbon footprint associated with these systems.

Revised regulatory systems should be based on the benefit/risk of the product, not on the process/technology used to deliver the product (Smyth 2017b; Caradus 2022; Gould et al. 2022). Supporting that benefit/risk analysis, a high level of trust is required in the organisations that evaluate and regulate GM crops (Siegrist 2000; Scott 2003; Ali et al. 2021), for society at large to accept the ruling and the use of GM technologies. To manage and understand potential risks associated with GM crops particular focus should include testing for:

1. Human and animal health and welfare impacts, including testing for allergenicity (EFSA GMO Panel 2022a); and
2. Impacts on beneficial non-target organisms, principally arthropods (Romeis et al. 2008).

An awareness of gene flows from GM crops needs to be also considered and understood.

In New Zealand, there is an ever-increasing list of foods from GM crops that can be sold (Food Standards Australia and New Zealand – FSANZ 2021), if appropriately labelled, but still the ability of farmers and growers to exploit the benefits of GM crops and forages is constrained (Caradus 2022). Adding to this inconsistency and lack of pragmatic logic is the fact that oil from nine GM events in canola (Brassica napus), and listed as approved by FSANZ, can be consumed as food by humans, but the by-product meal, left after the oil extraction process, cannot be consumed as feed by animals in New Zealand.

Above all, the provision of reliable and peer reviewed information and commentary is required to provide confidence that risk-tested GM crops can provide solutions and benefits to challenges facing the world with an ever-increasing population. It is critical that there is responsible reporting of agricultural technologies to realise their potential (Mehta and Vanderschuren 2021). There is no doubt that fact-based conversations are required, along with minds open to balancing risk and benefits, rather than holding to ideologies and polarised views.

This systematic review on the benefits and risks of GM crops leads to the conclusion that GM crops provide considerable benefits and are a valuable option that needs to be employed to solve many of the current challenges facing humankind, and as a result they will improve not simply economic outcomes, but also the environment. The GM technologies like many non-GM technologies can bring risks, but these can be monitored and quantified and allow decisions to be made about commercial, societal and environmental benefits, versus real risks.

Conflict of interest

The author is employed by Grasslanz Technology Ltd which has an R&D investment portfolio that includes both the genetic modification and gene editing of forages and microbes to provide mitigating solutions to current environmental and animal welfare issues facing New Zealand and other pastoral economies.

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