Genetic modification – benefits and risks for New Zealand grassland production systems

John R CARADUS

Grasslanz Technology Ltd, PB11008, Palmerston North, New Zealand
*Corresponding author: john.caradus@grasslanz.com

Highlights

- Genetic modification (GM) has been extensively used in crops for 25 years, but rarely has this resulted in commercial cultivars of grazed forages.
- Genetically modified plants will not solve all challenges confronting managed grasslands systems but have the potential to alleviate some, including those associated with environmental challenges.
- Delivery of new genetically modified cultivars does require consideration of consumer concerns that include food safety, environmental risks, and genetic perturbations.
- An issue that needs to be debated and resolved in NZ is the attitudinal positions taken by processing and marketing industries associated with products from pastoral agriculture. This would involve quantifying the comparative value of organic produce and the GM free status of the country across different market segments.
- Inconsistent approaches to regulating GM plants across different jurisdictions simply creates confusion.

Keywords: environment, gene editing, plant breeding, regulation, traits

Background

Fundamentally plant breeding is about expanding and exploiting the genetic potential of plants (Stoskopf et al. 2019). Over time this has included amongst others phenotypic selection, mutagenesis, genetic modification (GM) and now gene editing (Bowerman et al. 2023). In many crop species genetic modification has been a valuable option for delivering improved economic and environmental outcomes. However, while genetic modification has been extensively used to advance trait expression in crops, including grazed forages for animal feed, for 25 years it has rarely been used in commercialised cultivars of grazed grassland species. Worldwide, GM technologies have been adopted at a faster rate than any other recent crop technology (Raman 2017; Scheitrum et al. 2020). Despite the large government investment into GM technologies for use in grass and forage plants it has not been used outside of containment in New Zealand (Caradus 2008).

The aim here is to review why New Zealand has been slow to use GM technologies as another means of providing solutions for the pastoral sector. Traits manipulated using a range of genetic modification techniques that might have application and benefit in grassland systems will be reviewed, and regulatory concerns that need to be considered when adopting GM forage and pasture plants are discussed. Interestingly, 70 to 90% of GM crop production globally is used for animal feed (Flachowsky et al. 2012; Ritchie and Roser 2021). So if animals across the world, including those in USA, China and Europe are being fed GM crops (Baulcombe et al. 2014) what is the added value achieved by New Zealand in maintaining a GM free status? Although over a decade old, a useful summary of views from a variety of stakeholders is provided by the New Zealand Institute of Agricultural and Horticultural Science (AgScience 2010).

Definitions

Genetic modification is defined in New Zealand legislation as any organism in which any of the genes or other genetic material:

(a) have been modified by *in vitro* techniques; or
(b) are inherited or otherwise derived, through any number of replications, from any genes or other genetic material which has been modified by *in vitro* techniques (New Zealand Legislation 1996).

This definition therefore includes all **New Breeding Technologies** (NBT) (synonymous with the term New Genomic Techniques (NGT)) (Parisi and Rodriguez-Cerezo 2021) which includes:

- **genome or gene editing** to modify DNA at one or more specific sites using CRISPR, Zinc Finger Nucleases, TALENs or oligonucleotide-directed mutagenesis (RSNZ 2016; Sauer et al. 2016; Songstad et al. 2017; Es et al. 2019; Kumar et al. 2020);
  - **CRISPR Cas** (Bezie et al. 2021) delivers three types of outcomes - gene disruption or deletion

ISSN 2463-2872 (Print) ISSN 2463-2880 (Online) https://doi.org/10.33584/jnzg.2023.85.3654

(SDN1), gene correction or modification (SDN2), or DNA insertion (SDN3) (Doudna and Charpentier 2014; FAO 2022)
- **cisgenesis** (transferring a gene from the same or a closely related species) (Freddy et al. 2022; Hefferon 2022; Koul 2022);
- **intragenesis** (inserting a reorganised regulatory coding region of a gene from the same species) (Conner et al. 2007); and
- using **RNA-directed DNA methylation epigenetic processes** to change the activity of genes without changing a DNA sequence (Weinhold 2006; Schaart et al. 2016).

The word **transgenesis** describes the process of transferring exogenous DNA material or a gene (transgene) into an organism in such a way that the transgene is able to be passed onto the progeny of that organism.

In New Zealand the legal definition of genetic modification does not include:
- Phenotypic selection or what we know as conventional breeding including all mass selection and recurrent selection methods (Stoskopf et al. 2019);
- Interspecific hybridisation (Bowley and Taylor 1987);
- Polyploidy (Ranney 2006);
- Heterotic or F1 breeding breeding systems (Fujimoto et al. 2018);
- Chemical and radiation induced mutagenesis (Oladosu et al. 2016);
- Reverse genetics and breeding (Kumar et al. 2022); or
- Selection of genotypes with desired traits using genetic and molecular markers (Nadeem et al. 2018).

Manipulation of the genetics of crops and forages, mostly without precision or knowledge of genetic systems has been operating for millennia, and without legal regulation (Caradus 2023). The capability to introduce genes of known effect and with genetic methods that are increasingly precise and targeted has resulted in regulatory systems that has slowed delivery of new variation in many territories and most notably in New Zealand.

Challenges confronting grassland agricultural systems

Despite the importance of managed grassland systems for food production there are challenges in many countries concerning their economic, environmental, and societal impacts. In addition, climatic events and changes, competition for land use, biosecurity incursions, energy use efficiency, changing consumer preferences, and creation of new added-value food products all require grasslands systems to be modified using a number of technologies including both management and/ or genetic mitigations.

Genetically modified traits of potential benefit for grassland systems

GM plants will not solve all the apparent challenges confronting managed grasslands systems, but they have the potential to alleviate some. Solutions to some of these complex challenges using GM technologies are summarised in Table 1. This includes references to current work in forages and extrapolating from work undertaken in other crops offshore. Globally there have been over 800 commercialised GM events with 13 related to abiotic stress tolerance, 4 for altered growth or yield, 361 with herbicide tolerance, 29 with improved disease resistance, 310 for improved insect resistance, 1 with nematode resistance, 77 for modified product quality, and 33 for pollination control (ISAAA 2022a).

The intended and unintended consequences of GM crops and whether concerns are real or not, and if real are they manageable has been extensively reviewed (Caradus 2022a). The conclusion was "that GM plants are a valuable option for delivering improved economic and environmental outcomes through providing solutions for many of the challenges facing humanity". As an example, a meta-analysis of 147 studies on the benefits of food and feed crops determined that the adoption of GM technologies has decreased the use of chemical pesticides by 37%, increased crop yields by 22%, and increased farmer profits by 68% (Klümper and Qaim 2014).

Consumer concerns

The delivery of any new GM cultivar requires consideration of consumer concerns (Kendall et al. 1997; Caradus 2022a). These include:

1. Food safety. The consumption of any new foods or foods from GM crops either by animals or humans should be effectively and thoroughly tested for their impact on health and welfare. Many non-GM crops also contain potentially toxic or allergenic compounds (e.g., allergies to many plant pollens). 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 it has been argued that food from GM crops are as safe, or safer, than food derived from non-GM crops, (Halford and Shewry 2000).

Table 1 Examples of the application of GM technologies towards providing solutions to either issues currently facing the New Zealand pastoral sector, or opportunities that deliver a competitive advantage. Refer also Kumar et al. 2020.

Issue	Solution or trait	Plant species	Current situation	Country or region	Reference
Greenhouse gas emissions mitigation, and freshwater quality	Expression of condensed tannins (CT)	White clover *(Trifolium repens)*	*In vitro* proof of concept achieved; breeding for yield improvement with CT expression; field trials in USA and underway in Australia	New Zealand and Australia	Caradus et al. 2022c; Roldan et al. 2022
	High metabolisable energy ryegrass	Perennial ryegrass (*Lolium perenne)*	Field trials in USA	New Zealand	Winichayakul et al. 2020; Beechey-Gradwell et al. 2022
Animal health and welfare	Gene editing of alkaloid pathways	*Epichloë* fungal mutualist	Achieved and working towards agronomy trials in Australia	New Zealand and Australia	Miller et al. 2022
Drought tolerance	Improved water use efficiency	Maize (*Zea mays)*	Commercialised	USA	Chang et al. 2014; ISAAA 2016
Disease resistance	Alfalfa mosaic virus resistance	White clover	Not commercialised	Australia	Panter et al. 2012
	Bean golden mosaic virus resistance	Bean *(Phaseolus vulgaris)*	Commercialised	Brazil	Faria et al. 2006
	White clover mosaic resistance	White clover	Not commercialised	New Zealand	Voisey et al. 2001
Improved nutritional quality	Lignan modification	Lucerne *(Medicago sativa)*	Commercialised	USA	Barros et al. 2019
		Tall fescue *(Festuca arundinacea)*	Not commercialised	USA	Chen et al. 2004
	Improved amino acid balance	Subterranean clover *(T. subterraneum)*	Not commercialised	Australia	Tabe et al 1997
Pest resistance	Control of porina *(Wiseana spp.)* by using cry1B gene from Bt*.	White clover	Developed but never commercialised due to regulatory issues	New Zealand	Voisey et al. 1994
	30 pests controlled by Bt* transformed crops	Range of crops	Some commercialised	Latin America	Blanco et al. 2016
	Control of the European maize borer	Maize	Commercialised	USA	Hutchison et al. 2010
	Control of maize rootworms *(Diabrotica spp.)*	Maize	Commercialised	Meta-analysis of 10 studies	Pellegrino et al. 2018

* Bt is *Bacillus thuringiensis*

2. Environmental risks, which have been described as increased herbicide tolerance of weeds, overuse of herbicides and pesticides, secondary pests becoming more dominant, impacts on non-target organisms, resistant insect populations, increased weediness, negative impacts on biodiversity, transgene escape into wild or non-GM populations, negative impacts on rhizosphere microorganism, and/ or gene transfer to consumers from GM food and feed.
3. Genetic perturbations leading to production of unintended compounds, new disease, or antibiotic resistance resulting from horizontal gene flow.

However, after 20 years of GM crop use most of the risks associated with the use of GM crops have proven to be low to non-existent (Vega Rodríguez et al. 2022). In USA, GM crops have been used for either animal feed or human food for over 25 years with no proven recorded cases of health-related issues (Nicolia et al. 2014; Abdul Aziz et al. 2022).

Consumer concerns about using GM crops and forages in New Zealand has been reviewed (Caradus 2022b). It concludes that “while there will always be a proportion of consumers against the use of GM in food production, the published evidence would suggest that the use of GM plants in New Zealand for food production will have no long-term deleterious effects in overseas markets”. Current attitudes towards gene editing and GM crops in New Zealand have been provided by two public surveys by Research First (2022, 2023). These have shown that 72% either support or are neutral for consuming GM foods if they contain less pesticide and better nutrition, and that 79% either support or are neutral for gene editing food production in New Zealand.

Industry concerns

Perhaps one of the bigger and more complex issues are the benefits versus the risks of using GM technologies in New Zealand. This requires debate and resolution across the primary sector processing, marketing, and exporting industries. There is a view that “use of GM grasses is likely to encounter strong resistance from some markets overseas as well as within New Zealand” (Reisinger et al. 2018).

So the question is – would market access be an issue for milk and meat products from animals fed GM forages? New Zealand’s major market are China, Australia, USA, Japan and collectively the European Union. Their regulatory systems and use of GM crops is summarised in Table 2. An additional concern might be how animals fed GM forages may affect the general national and international view of “NZ clean and green” image and any associated risk to other type of industry important for New Zealand economy (i.e., side effects), e.g., tourism? A recent survey of New Zealanders (Research First 2023) indicated that 39% believe that introducing GM food production to NZ would have a positive impact, or no impact, on New Zealand’s image; with 39% believing there would be some impact and 23% a very negative impact. A decade old survey of first-time visitors to New Zealand found that the introduction of GM crops into New Zealand was highly unlikely to create lasting damage to perceptions in overseas markets of the image of New Zealand as a source of high-quality food products or as a highly desirable scenic and “clean green” tourist destination (Knight et al. 2013).

China, New Zealand’s biggest market, imports 44% of dairy, 90% of logs, and 41% of meat exported by New Zealand (Xinhua 2021). China is also Australia’s major export market for meat, wine, wool, fruit and nuts, seafood, and grains, and dairy, despite Australia permitting the production of some GM crops (Ishii and Araki 2017), buying more of Australia’s agricultural produce than any other country (Department of Foreign Affairs and Trade 2018). Additionally, China itself has the sixth highest area, of 28 countries known to grow GM crops, under commercial cultivation of GM crops (Ishii and Araki 2017).

If New Zealand grew and used GM forages in pastoral agriculture would market opportunities be lost? As a comparative example “when Canada introduced GM canola, it lost access to the EU market for its canola seed. However, Canada has found ready markets for its increased canola supplies elsewhere, particularly in Mexico, the United States, Pakistan, and China” (DAFF 2007). Additionally, evidence does not support the view that South Australian farmers enjoy better access in European Union non-GM grain markets, and since 2012 there has been no premium for grain from South Australia despite it (up until recently) being the only mainland state with a GM crop moratorium (Anderson 2019).

Europe is also an important market from New Zealand, and Europe has a very restrictive regulatory system for GM crops and foods, similar in many ways to New Zealand. However, there has been a recent increase in lobbying within the European Union to determine if the current legislation if fit for purpose (Euobserver 2021; Albert 2022). Additionally, in Europe most pig, chicken and to a lesser extent cattle production relies on the importation of 15M tons of soybean meal annually from North and South America (Tagliabue 2017; Shahbandeh 2022) (90% of which is GM) (Henseler et al. 2013; Sieradzki et al. 2021). Notably in 2022 the European Food Safety Authority (EFSA) authorised herbicide tolerant GM canola, cotton, and soybeans crops and renewed the authorization for GM cotton used for food and animal feed (Science Business 2021; ISAAA 2022b).

Table 2 Regulatory system and use of GM crops by New Zealand's major export market countries. Refer to Turnbull et al. 2021 for further information.

Trading partner	Regulatory system	GM use	Reference
China		17 products - GM soybean, maize, canola, cotton seeds, and tomatoes were approved for import if labelled in 2002: imports over 6 times more GM soybean than the next highest importer, the European Union; second largest GM cotton producer in world	Turnbull et al. 2021; Shahbandeh 2022; Xiao and Kerr 2022
Australia	Process based; SDN1 gene edits not regulated	3 GM crops grown - cotton, canola, and safflower *(Carthamus tinctorius).*	OGTR 2021; Schmidt et al. 2021
USA	Product based; SDN1 gene edits not regulated	Has largest area of GM crops; GM food consumed widely for over 25 years	Wolt and Wolf 2018; Schmidt et al. 2021
Japan	Product based; SDN1 gene edits not regulated	While Japan has approved eight types of GM crops for commercial use farmers are reluctant to grow them; commercial use in ornamental crops	FFTC 2017; Schmidt et al.2021; Turnbull et al. 2021
European Union	Process based; Gene editing regulated as GM	Restricted use of GM crops but imports large quantities of GM feed for animals and has approved growing of some GM crops	Henseler et al. 2013; ISAAA 2022b

The UK, having exited the European Union, has recently passed a law (the Genetic Technology (Precision Breeding) Act) allowing key technologies which include gene editing to improve UK food security, reduce pesticide use, and enhance climate-resilience in cropping (DEFRA 2023). This Act provides for a new science-based and streamlined regulatory system that will be introduced to facilitate greater research and innovation in precision breeding, but with stricter regulations remaining in place for genetically modified organisms.

Regulatory challenges

Science-based risk management and assessment regulatory frameworks have been in place to oversee commercialisation and use of GM crops since their advent (Craig et al. 2008). An extensive review (Caradus 2022a) of the intended and unintended consequences of GM crops concluded that managing 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 2022);
2. Impacts on beneficial non-target organisms, principally arthropods (Romeis et al. 2008); and
3. An awareness of gene flows from GM crops needs to be also considered and understood.

The recent use of New Breeding Technologies has resulted in some countries re-evaluating their regulatory processes. Accordingly, nine out of the largest 10 countries by population have either paved a way or stated intentions to open up for easy use of gene edited plants in commercial agriculture (Sprink et al. 2022). Unlike the European Union and New Zealand many countries are now either not regulating or seriously considering not regulating SDN1 and in some cases SDN2 gene edits as genetically modified organisms (Buchholzer and Frommer 2022).

Coexistence of GM and non-GM crops and forages

Coexistence of GM crops with non-GM crops is a significant area of contention, and particularly for perennial outcrossing plants which includes most of the forage and pasture species used in New Zealand. The implementation of a coexistence policy is considered to have negative impact on farmers' attitudes towards adoption of GM crops (Areal et al. 2011). Managing gene flow from an outcrossing species is challenging if not impossible. Therefore the focus should be more on risk analysis of any likely 'invasiveness' of the transgenic plants and any 'mitigation' options available to reduce their impact on natural, as well as agricultural systems (Kareiva et al. 1994). Requirements for a minimum distance between GM and non-GM crops varies between countries and coexistence strategies for outcrossing forages have been reviewed (Christey and Woodfield 2001; Smith and Spangenberg 2016).

Apparent contradictions and inconsistencies

The use of GM food and feeds has often resulted in polarised views and can result in the selective use of information depending on ones' views, or simply due to an unwillingness to recognise the contradictions associated with some views. These include:

1. New Zealand food businesses importing and selling (with appropriate labelling) about 90 GM foods listed on FSANZ website, some since the year 2000 (FSANZ 2022) – versus - farmers in New Zealand being unable to grow any GM crops due to regulations legislated under the current HSNO Act (New Zealand Legislation 1996).
2. Primary sector exporters believe that New Zealand's high value markets will not take our products if GM crops and forages were fed to animals (RSNZ 2018; Hall 2021); a view reflected by governments - "our cautious approach is that New Zealand is an exporter of billions of dollars of food products and we need to be mindful of market perceptions as well as the science" (New Zealand Government 2016) – versus – most if not all of our major markets either grow or import GM crops and forages to feed their animals (Table 2) (Caradus 2022b).
3. GM technologies are patented and result in license fees and increased costs (GE free NZ 2023) - versus – increased on-farm profitability for those using GM crops. A review of economic benefits has been provided by Caradus (2022a); one example, a survey of 98 peer-reviewed studies that compared the economic performance of GM crops to their conventional counterparts with 71 indicating a positive impact, 11 neutral and 16 negative (Carpenter 2010).
4. A GM-free status confers a premium in international markets – versus – an absence of evidence of a GM-free status providing any economic benefit, e.g. the opportunity cost due to some States in Australia delaying adoption of GM canola has been estimated to have resulted in foregone output of 1.1 million T of canola and a net economic loss to canola farmers of AU$485.6 million (Biden et al. 2018).
5. Mutagenesis using targeted gene editing is regulated in New Zealand – versus – random mutagenesis generated using radiation or chemicals is unregulated (Caradus 2023).
6. GM foods are deleterious to human health (Pusztai 2001, 2002) – versus – after 25 years of human consumption of GM foods across many countries there have been no proven cases of human health and welfare issues of concern attributable to GM technologies (Panchin and Tuzhikov 2017).
7. GM technologies are rejected by environmentalists and organic farming groups (Wickson et al. 2016; IFOAM Organics international 2021) – versus – GM technologies may provide a means to reduce environmental impacts from agriculture (Purnhagen et al. 2021). There is a view that "in light of New Zealand's 'clean and green' branding some interviewees thought a continued reluctance to allow gene editing that could potentially reduce environmental impacts is somewhat incongruous" (Davies et al. 2018).

Conclusions

Inconsistent approaches to regulating GM plants across different jurisdictions and the situation where some countries allow the consumption of GM food but do not allow GM plants to be grown simply creates unnecessary confusion. New Zealand is a good example, where the FSANZ website lists 90 GM food that can be imported and sold, with appropriate labelling, but none can be grown by New Zealand farmers. However, while balancing risk and benefit of any new technological advance is important, regulators must dispense with process driven regulatory systems for more informed and nuanced product-based regulatory processes. Ideally, regulatory systems should be based on the benefit/ risk of the product not on the process/ technology used to deliver the product (Smyth 2017; Turnbull et al. 2021; Gould et al. 2022).

REFERENCES

Abdul Aziz M, Brini F, Rouached H, Masmoudi K. 2022. Genetically engineered crops for sustainably enhanced food production systems. *Frontiers in Plant Science. 13*: Article 1027828. https://doi.org/10.3389/fpls.2022.1027828

AgScience 2010. Genetic modification revisited. *Issue 36*. New Zealand Institute of Agricultural and Horticultural Science. Pp. 24. [Accessed 1 April 2023]. https://www.agscience.org.nz/wp-content/uploads/AgScience-PDF/agscience-36-web.pdf \

Albert H. 2022. GMO Regulations in Europe Are "Not Fit for Purpose". [Accessed 1 April 2023]. https://www.labiotech.eu/in-depth/gmo-regulations-europe/

Anderson K. 2019. Independent review of the South Australian GM food crop moratorium. Report to the SA Minister for Primary Industries and Regional Development. Pp. 76.[Accessed 26 March 2023]. www.adelaide.edu.au/saces/ua/media/388/Independent_Review_0319.pdf

Areal FJ, Riesgo L, Rodríguez-Cerezo E. 2013. Economic and agronomic impact of commercialized GM crops: a meta-analysis. *Journal of Agricultural Science 151*: 7–33. doi:10.1017/S0021859612000111

Barros J, Temple S, Dixon RA. 2019. Development and commercialization of reduced lignin alfalfa. *Current Opinion in Biotechnology 56*:48-54. https://doi.org/10.1016/j.copbio.2018.09.003

Baulcombe D, Dunwell J, Jones J, Pickett J, Puigdomenech P. 2014. GM Science Update: A report to the Council for Science and Technology. [Accessed 26 March 2023]. https://centaur.reading.ac.uk/36228/1/GM%20Science%20Update%20-%20Report%20to%20CST%20110314.pdf

Beechey-Gradwell Z, Kadam S, Bryan G, Cooney L, Nelson K, Richardson K, Cookson R, Winichayakul S, Reid M, Anderson P, Crowther T, Zou X, Maher D, Xue H, Scott R, Allan A, Stewart A, Roberts N. 2022. Lolium perenne engineered for elevated leaf lipids exhibits greater energy density in field canopies under defoliation. *Field Crops Research 275*: Article 108340. https://doi.org/10.1016/j.fcr.2021.108340

Bezie, Y, Tilahun T, Atnaf M, Taye M. 2021. The potential applications of site-directed mutagenesis for crop improvement: a review. *Journal of Crop Science and Biotechnology 24*: 229–244. https://doi.org/10.1007/s12892-020-00080-3

Biden S, Smyth SJ, Hudson D. 2018. The economic and environmental cost of delayed GM crop adoption: The case of Australia's GM canola moratorium. GM Crops. *Food 9*: 13-20. https://doi.org/10.1080/21645698.2018.1429876

Blanco CA, Chiaravalle W, Dalla-Rizza M, Farias JR, García-Degano MF, Gastaminza G, Mota-Sánchez D, Murúa MG, Omoto C, Pieralisi BK, Rodríguez J, Rodríguez-Maciel JC, Terán-Santofimio H, Terán-Vargas AP, Valencia SJ, Willink E. 2016. Current situation of pests targeted by Bt crops in Latin America. Current Opinion. *Insect Science 15*: 131-138. https://doi.org/10.1016/j.cois.2016.04.012

Bowerman AF, Byrt CS, Roy SJ, Whitney SM, Mortimer JC, Ankeny RA, Gilliham M, Zhang D, Millar AA, Rebetzke GJ, Pogson BJ. 2023. Potential abiotic stress targets for modern genetic manipulation, *The Plant Cell 35*: 139–161. https://doi.org/10.1093/plcell/koac327

Bowley SR, Taylor NL. 1987. Introgressive hybridization. *In*: Christie BR, (editor), CRC Handbook of Plant Science in Agriculture. Boca Raton FL, USA. 1: 23-59.

Buchholzer M, Frommer WB. 2023. An increasing number of countries regulate genome editing in crops. New Phytologist 237: 12-15. https://doi.org/10.1111/nph.18333

Caradus JR. 2008. An opportunity lost and sorting fact from fiction. *Proceedings of the New Zealand Grassland Association 70*: 1-6. https://doi.org/10.33584/jnzg.2008.70.2717

Caradus JR. 2022a. Intended and unintended consequences of genetically modified crops – myth, fact and/or manageable outcomes? *New Zealand Journal of Agricultural Research 65*: http://dx.doi.org/10.1080/00288233.2022.2141273

Caradus JR. 2022b. Impacts of growing and utilising genetically modified crops and forages – a New Zealand perspective. *New Zealand Journal of Agricultural Research 65*: https://doi.org/10.1080/00288233.2022.2077380

Caradus JR. 2023. Perceptions of Plant Breeding – from 'Phenotypic Selection' to 'Genetic Modification' and 'New Breeding Technologies'. *New Zealand Journal of Agricultural Research 66*: https://doi.org/10.1080/00288233.2023.2187425

Caradus JR, Voisey CR, Cousin GR, Kaur R, Woodfield DR, Blanc A, Roldan MB. 2022c. The hunt for the "holy grail": condensed tannins in the perennial forage legume white clover (Trifolium repens L.). *Grass and Forage Science 77*: 111– 123. https://doi.org/10.1111/gfs.12567

Carpenter JE. 2010. Peer-reviewed surveys indicate positive impact of commercialized GM crops. *Nature Biotechnology 28*: 320-321. https://doi.org/10.1038/nbt0410-319

Chang J, Clay DE, Hansen SA, Clay SA, Schumacher TE. 2014. Water stress impacts on transgenic drought-tolerant corn in the northern Great Plains. *Agronomy Journal 106*:125–130. https://doi.org/10.2134/agronj2013.0076

Chen L, Auh CK, Dowling P, Bell J, Lehmann D, Wang ZY. 2004. Transgenic down-regulation of caffeic acid O-methyltransferase (COMT) led to improved digestibility in tall fescue (*Festuca arundinacea*). *Functional Plant Biology 31*: 235-245. https://doi.org/10.1071/FP03254

Christey M, Woodfield D. 2001. Coexistence of genetically modified and non-genetically modified crops. Crop and Food Research Confidential Report No. 427, p. 1-71. Report prepared for the Ministry for the Environment. June 2001. [Accessed 30 March 2023]. https://environment.govt.nz/assets/Publications/Files/coexistence-feb01.pdf

Conner AJ, Barrell PJ, Baldwin SJ, Lokerse AS, Cooper PA, Erasmuson AK, Nap JP, Jacobs JME 2007. Intragenic vectors for gene transfer without foreign DNA. *Euphytica 154*: 341-353. https://doi.org/10.1007/s10681-006-9316-z

Craig W, Tepfer M, Degrassi G, Ripandelli D. 2008. An overview of general features of risk assessments of genetically modified crops. *Euphytica 164*: 853-880. https://doi.org/10.1007/s10681-007-9643-8

DAFF 2007. Biotechnology – Market acceptance of GM Canola. [Accessed 29 March 2023]. https://www.awe.gov.au/sites/default/files/sitecollectiondocuments/ag-food/biotech/gm-market-acceptance-final.pdf

Davies P, Moore D, Yarrall D, 2018. Current land based farming systems research and future challenges. Report to the Ministry for Business, Innovation and Employment. Pp. 50. [Accessed 1 April 2023]. https://www.mbie.govt.nz/assets/b0531a59b2/land-based-farm-systems.pdf

Department of Foreign Affairs and Trade 2018. China-Australia Free-Trade Agreement [Accessed 26 March 2023]. https://www.dfat.gov.au/trade/agreements/in-force/chafta/fact-sheets/Pages/chafta-outcomes-at-a-glance

DEFRA 2023. Genetic Technology Act key tool for UK food security. Department for Environment, Food and Rural Affairs. [Accessed 30 March 2023]. https://www.gov.uk/government/news/genetic-technology-act-key-tool-for-uk-food-security

Doudna JA, Charpentier E. 2014. The new frontier of genome engineering with CRISPR-Cas9. *Science 346*: Article 1258096. https://www.science.org/doi/10.1126/science.1258096

EFSA GMO Panel 2022. Mullins E, Bresson J-L, Dalmay T, Dewhurst IC, Epstein MM, George Firbank L, Guerche P, Hejatko J, Naegeli H,Nogue F, Rostoks N, Sanchez Serrano JJ, Savoini G, Veromann E, Veronesi F, Fernandez Dumont A, Moreno FJ, et al. Scientific Opinion on development needs for the allergenicity and protein safety assessment of food and feed products derived from biotechnology. *EFSA Journal 20*:7044, p.1-38. https://doi.org/10.2903/j.efsa.2022.7044

Eş I, Gavahian M, Marti-Quijal FJ, Lorenzo JM, Khaneghah AM, Tsatsanis C, Kampranis SC, Barba FJ. 2019. The application of the CRISPR-Cas9 genome editing machinery in food and agricultural science: Current status, future perspectives, and associated challenges. *Biotechnology Advances 37*: 410-421. https://doi.org/10.1016/j.biotechadv.2019.02.006

Euobserver 2021. Revealed: the new lobbying effort to deregulate GMOs. [Accessed 1 April 2023]. https://euobserver.com/green-economy/151375

FAO. 2022. Gene editing and agrifood systems. Food and Agriculture Organization of the United Nations, Rome. 86p. https://doi.org/10.4060/cc3579en

Faria JC, Albino MMC, Dias BBA, Cancado LJ, Cunha NB, Silva LM, Vianna GR, Aragão FJL. 2006. Partial resistance to Bean golden mosaic virus in a transgenic common bean (*Phaseolus vulgaris* L.) line expressing a mutated rep gene. *Plant Science 171*: 565–571. https://doi.org/10.1016/j.plantsci.2006.06.010

FFTC 2017. The Japanese Policy for Genetically Modified Food. [Accessed 29 January 2023]. https://ap.fftc.org.tw/article/1169

Flachowsky G, Schafft H, Meyer U. 2012. Animal feeding studies for nutritional and safety assessments of feeds from genetically modified plants: a review. *Journal für Verbraucherschutz und Lebensmittelsicherhei. 7*: 179–194. https://doi.org/10.1007/s00003-012-0777-9

Freddy BO, Aimé DN, Jacques LNB, Sébastien LN. 2022. Cisgenesis and plant breeding: A review. *In*: Chaurasia A, Kole C. (editors) Cisgenic Crops: Potential and Prospects. Concepts and Strategies in Plant Sciences. Springer, Cham. Pp. 79-87. https://doi.org/10.1007/978-3-031-06628-3_5

FSANZ 2022. Food Standard Australia New Zealand – Current GM applications and approvals. [Accessed 26 March 2023]. https://www.foodstandards.gov.au/consumer/gmfood/applications/Pages/default.aspx

Fujimoto R, Uezono K, Ishikura S, Osabe K, Peacock WJ, Dennis ES. 2018. Recent research on the mechanism of heterosis is important for crop and vegetable breeding systems, *Breeding Science 68*: 145-158. https://doi.org/10.1270/jsbbs.17155

GE Free NZ 2023. Federated Farmers' Life Sciences Push to Loosen GE Regulations is a Threat to Farmers and Exports. [Accessed 26 March 2023]. http://press.gefree.org.nz/press/20230318.htm

Gould F, Amasino RM, Brossard D, Buell CR, Dixon RA, Falck-Zepeda JB, Gallo MA, Giller KE, Glenna LL, Griffin T, Magraw D. 2022. Toward product-based regulation of crops. *Science 377*: 1051-1053. https://doi.org/10.1126/science.abo3034

Halford NG, Shewry PR. 2000. Genetically modified crops: methodology, benefits, regulation and public concerns. *British Medical Bulletin 56*: 62-73. https://doi.org/10.1258/0007142001902978

Hall, D. 2021. Increasing Pressures on Farming from the Outside World. *In*: Hall D. Ed. Agricultural Economics and Food Policy in New Zealand. Chapter 24, Pp. 373-389. Palgrave Studies in Agricultural Economics and Food Policy. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-86300-5_24

Hefferon K. 2022. Cisgenesis of crops. *In*: Chaurasia A, Kole C, (editors) Cisgenic Crops: Potential and Prospects. Concepts and Strategies in Plant Sciences. Springer, Cham. Pp. 67-78. https://doi.org/10.1007/978-3-031-06628-3_4

Henseler M, Piot-Lepetit I, Ferrari E, MelladoAG, Banse M, Grethe H, Parisi C, Hélaine S. 2013. On the asynchronous approvals of GM crops: Potential market impacts of a trade disruption of EU soy imports. *Food Policy 41*: 166-176. https://doi.org/10.1016/j.foodpol.2013.05.005

Hutchison WD, Burkness EC, Mitchell PD, Moon RD, Leslie TW, Fleischer SJ, Abrahamson M, Hamilton KL, Steffey KL, et al. 2010. Areawide suppression of European corn borer with Bt maize reaps savings to non-Bt maize growers. *Science 330*: 222-225. https://

www.ncbi.nlm.nih.gov/pubmed/20929774

IFOAM Organics international 2021. The principle of care. [Accessed 1 April 2023]. https://www.ifoam.bio/why-organic/principles-organic-agriculture/principle-care

ISAAA 2016. Global Status of Commercialized Biotech/GM Crops: 2016. ISAAA Brief No. 52.2017. International Service for the Acquisition of Agri-biotech Applications. Ithaca, NY. [Accessed 1 April 2023]. http://www.isaaa.org/resources/publications/briefs/52/download/isaaa-brief-52-2016.pdf

ISAAA 2022a. GM Approval Database – Commercial GM traits list. International Service for the Acquisition of Agri-biotech Applications. Ithaca, NY. [Accessed 1 April 2023]. https://www.isaaa.org/gmapprovaldatabase/commercialtraitlist/default.asp

ISAAA 2022b. European Commission Authorizes 3 GM Crops; Renews Authorization for GM Cotton. [Accessed 29 March 2023]. https://www.isaaa.org/kc/cropbiotechupdate/article/default.asp?ID=19411

Ishii T, Araki M. 2017. A future scenario of the global regulatory landscape regarding genome-edited crops. GM Crops. *Food 8*: 44-56. https://doi.org/10.1080/21645698.2016.1261787

Kareiva P, Morris W, Jacobi CM. 1994. Studying and managing the risk of cross-fertilization between transgenic crops and wild relatives. *Molecular Ecology 3*: 15-21. https://doi.org/10.1111/j.1365-294X.1994.tb00037.x

Kendall HW, Beachy R, Eisner T, Gould F, Herdt R, Raven PH, Schell JS, Swaminathan MS. 1997. Bioengineering of crops: Report of the World Bank Panel on transgenic crops. *Environmental and Socially Sustainable Development Studies and Monograph Series 23*. p.30. ISBN-13: ‎978-0821340738

Klümper W, Qaim M. 2014. A Meta-Analysis of the Impacts of Genetically Modified Crops. *PLoS ONE 9*: e111629, http://dx.plos.org/10.1371/journal.pone.0111629

Knight JG, Clark A, Mather DW. 2013. Potential damage of GM crops to the country image of the producing country. GM Crops and Food, 4:151-157. https://doi.org/10.4161/gmcr.26321

Koul B. 2022. Cisgenics and crop improvement. *In*: Cisgenics and Transgenics. Pp. 107-129. Springer, Singapore. https://doi.org/10.1007/978-981-19-2119-3_3

Kumar J, Kumar A, Sen Gupta D, Kumar S, DePauw RM. 2022. Reverse genetic approaches for breeding nutrient-rich and climate-resilient cereal and food legume crops. *Heredity 128*: 473–496. https://doi.org/10.1038/s41437-022-00513-5

Kumar K, Gambhir G, Dass A, Tripathi AK, Singh A, Jha AK, Yadava P, Choudhary M, Rakshit S. 2020. Genetically modified crops: current status and future prospects. *Planta 251*: Article 91. https://doi.org/10.1007/s00425-020-03372-8

Miller TA, Hudson DA, Johnson RD, Singh JS, Mace WJ, Forester NT, Maclean PH, Voisey CR, Johnson LJ. 2022. Dissection of the epoxyjanthitrem pathway in Epichloë sp. LpTG-3 strain AR37 by CRISPR gene editing. *Frontiers in Fungal Biology 3*: Article 944234. https://www.frontiersin.org/articles/10.3389/ffunb.2022.944234

Nadeem MA, Nawaz MA, Shahid MO, Doğan Y, Comertpay G, Yıldız M, Hatipoğlu R, Ahmad F, Alsaleh A, Labhane N, Özkan H, Chung G, Baloch FS. 2018. DNA molecular markers in plant breeding: current status and recent advancements in genomic selection and genome editing. *Biotechnology and Biotechnological Equipment 32*: 261-285. https://doi.org/10.1080/13102818.2017.1400401

New Zealand Government. 2016. GMO Regulations Clarified. [Accessed 26 March 2023]. https://www.beehive.govt.nz/release/gmo-regulations-clarified

New Zealand Legislation 1996. Hazardous Substances and New Organisms Act 1996. [Accessed 18 March 2023]. https://legislation.govt.nz/act/public/1996/0030/latest/DLM381228.html

Nicolia A, Manzo A, Veronesi F, Rosellini D. 2014. An overview of the last 10 years of genetically engineered crop safety research. *Critical Reviews in Biotechnology 34*: 77-88. https://doi.org/10.3109/07388551.2013.823595

OGTR 2021. Genetically modified (GM) crops in Australia. Pp. 2. [Accessed 1 April 2023]. https://www.ogtr.gov.au/sites/default/files/files/2021-06/11_-_genetically_modified_gm_crops_in_australia.pdf

Oladosu Y, Rafii MY, Abdullah N, Hussin G, Ramli A, Rahim HA, Miah G, Usman M.2016. Principle and application of plant mutagenesis in crop improvement: a review. *Biotechnology and Biotechnological Equipment 30*: 1-16. https://doi.org/10.1080/13102818.2015.1087333

Parisi C, Rodríguez-Cerezo E. 2021. Current and future market applications of new genomic techniques. EUR 30589 EN. Publications Office of the European Union: Luxembourg. Pp. 52. doi:10.2760/02472, JRC123830.

Raman R. 2017. The impact of Genetically Modified (GM) crops in modern agriculture: A review. *GM Crops and Food 8*: 195–208. https://doi.org/10.1080/21645698.2017.1413522

Panchin AY, Tuzhikov AI. 2017. Published GMO studies find no evidence of harm when corrected for multiple comparisons. *Critical Reviews in Biotechnology 37*: 213-217. https://doi.org/10.3109/07388551.2015.1130684

Panter S, Chu PG, Ludlow E, Garrett R, Kalla R, Jahufer

MZZ, de Lucas Arbiza A, Rochfort S, Mouradov A, Smith KF, Spangenberg G. 2012. Molecular breeding of transgenic white clover (*Trifolium repens* L.) with field resistance to Alfalfa mosaic virus through the expression of its coat protein gene. *Transgenic Research 21*: 619–632. https://doi.org/10.1007/s11248-011-9557-z

Pellegrino E, Bedini S, Nuti M, Ercoli L. 2018. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: a meta-analysis of 21 years of field data. *Scientific Reports 8*: Article 3113. https://doi.org/10.1038/s41598-018-21284-2

Purnhagen KP, Clemens S, Eriksson D, Fresco LO, Tosun J, Qaim M, Visser RG, Weber AP, Wesseler JH, Zilberman D. 2021. Europe's farm to fork strategy and its commitment to biotechnology and organic farming: Conflicting or complementary goals? *Trends in Plant Science 26*: 600-606. https://doi.org/10.1016/j.tplants.2021.03.012

Pusztai A. 2001. Genetically modified foods: Are they a risk to human/animal health? *Action Bioscience* [Accessed 1 April 2023]. https://www.globalmagazine.info/sites/default/files/PDF/pusztai-gm-foods-risk-human-animal-health-2001.pdf

Pusztai A. 2002. Can science give us the tools for recognizing possible health risk of GM? *Nutrition and Health 16*: 73-84. https://doi.org/10.1177/026010600201600202

Ranney TG. 2006. Polyploidy: From evolution to new plant development. *Proceedings of the International Plant Propagators' Society 56*: 137-142.

Reisinger A, Clark H, Abercrombie R, Aspin M, Ettema P, Harris M, Hoggard A, Newman M, Sneath G. 2018. Future options to reduce biological GHG emissions on-farm: critical assumptions and national-scale impact. Report to the Biological Emissions Reference Group (BERG) - a partnership between New Zealand's agricultural sector and the Government Pp. 80. [Accessed 26 March 20123]. https://www.mpi.govt.nz/dmsdocument/32128/direct

Research First 2022. Public perceptions of gene editing. [Accessed 18 March 2023]. https://researchfirst.co.nz/wp-content/uploads/Gene-Editing-July-2022_v1.1-twopager.pdf

Research First 2023. Genetically modified foods. [Accessed 18 March 2023]. https://researchfirst.co.nz/wp-content/uploads/31-Genetically-Modified-Foods-March-2023_v1.1.pdf/

Ritchie H, Roser M. 2021. Forests and Deforestation. Published online at OurWorldInData.org. [Accessed 26 March 2023]. https://ourworldindata.org/forests-and-deforestation

Roldan MB, Cousins G, Muetzel S, Zeller WE, Fraser K, Salminen J-P, Blanca A, Kaur R, Richardson K, Maher D, et al. 2022. Condensed tannins in white clover (Trifolium repens) foliar tissues expressing the transcription factor TaMYB14-1 bind to forage protein and reduce ammonia and methane emissions in vitro. *Frontiers in Plant Science 12*: Article 777354. https://doi.org/10.3389/fpls.2021.777354

Romeis J, Bartsch D, Bigler F, Candolfi MP, Gielkens M, Hartley SE, Hellmich RL, Huesing JE, Jepson PC, Layton R, Quemada H. 2008. Assessment of risk of insect-resistant transgenic crops to nontarget arthropods. *Nature Biotechnology 26*: 203-208. https://doi.org/10.1038/nbt1381

RSNZ 2016. Gene Editing: Evidence Update. Pp. 9. [Accessed 18 March 2023]. https://www.royalsociety.org.nz/assets/documents/Gene-editing-evidence-update2.pdf

RSNZ 2018. Gene editing in the primary industries: Technical Paper. Pp. 34. [Accessed 1 April 2023]. https://royalsociety.org.nz/assets/Uploads/Gene-editing-in-primary-industries-technical-paper.pdf

Sauer NJ, Mozoruk J, Miller RB, Warburg ZJ, Walker KA, Beetham PR, Schöpke CR, Gocal GFW. 2016. Oligonucleotide-directed mutagenesis for precision gene editing. *Plant Biotechnology Journal 14*: 496–502. https://doi.org/10.1111/pbi.12496

Schaart JG, van de Wiel CCM, Lotz LAP, Smulders MJM. 2016. Opportunities for products of New Plant Breeding Techniques. *Trends in Plant Science 21*: 438-449. https://doi.org/10.1016/j.tplants.2015.11.006

Scheitrum D, Schaefer KA, Nes K. 2020. Realized and potential global production effects from genetic engineering, *Food Policy 93*: Article 101882. https://doi.org/10.1016/j.foodpol.2020.101882

Schimdt SM, Belisle M, Frommer WB. 2020. The evolving landscape around genome editing in agriculture. *EMBO Reports 21*: Article e50680 https://doi.org/10.15252/embr.202050680

Science Business 2021. Scientists and industry cheer outcome of Commission study on gene editing. [Accessed 1 April 2023]. https://sciencebusiness.net/news/scientists-and-industry-cheer-outcome-commission-study-gene-editing

Shahbandeh M. 2022. Import volume of soybeans worldwide in 2021/22, by country. [Accessed 26 March 2023]. https://www.statista.com/statistics/612422/soybeans-import-volumeworldwide-by-country/

Sieradzki Z, Mazur M, Król B, Kwiatek K. 2021. Prevalence of genetically modified soybean in animal feedingstuffs in Poland. *Journal of Veterinary Research. 65*: 93-99. https://doi.org/10.2478/jvetres-2021-0012

Smith K, Spangenberg G. 2016. Considerations for managing agricultural co-existence between transgenic and non-transgenic cultivars of outcrossing perennial forage plants in dairy pastures. *Agronomy 6*: Article 59. doi: 10.3390/agronomy6040059

Smyth SJ. 2017. Canadian regulatory perspectives on genome engineered crops. *GM Crops and Food 8*: 35–43. https://doi.org/10.1080/21645698.2016.1257468

Songstad DD, Petolino JF, Voytas DF, Reichert NA. 2017. Genome Editing of Plants, *Critical Reviews in Plant Sciences 36*: 1-23. https://doi.org/10.1080/07352689.2017.1281663

Sprink T, Wilhelm R, Hartung F. 2022. Genome editing around the globe: An update on policies and perceptions. *Plant Physiology 190*: 1579–1587. https://doi.org/10.1093/plphys/kiac359

Stoskopf NC, Tomes DT, Christie BR. 2019. *Plant breeding: theory and practice*. Routledge Taylor and Francis Group, London, and New York. Pp. 531. ISBN: 13:978-0-367-28301-8 (hbk)

Tabe LI, Molvig LI, Khan RA, Schroeder HA, Gollasch ST, Wardley-Richardson TE, Moore AN, Craig S, Spencer D, Eggum B, Higgins TJ. 1997. Modifying the sulphur amino-acid content of protein in transgenic legumes. *Sulphur Metabolism in Higher Plants*. Cram WJ, et al. (Editors). Backhuys Publishers, Leiden, The Netherlands. Pp. 87-93.

Tagliabue G. 2017. The EU legislation on “GMOs” between nonsense and protectionism: An ongoing Schumpeterian chain of public choices. *GM Crops and Food 8*: 57-73. https://doi.org/10.1080/21645698.2016.1270488

Turnbull C, Lillemo M, Hvoslef-Eide TAK. 2021. Global Regulation of Genetically Modified Crops Amid the Gene Edited Crop Boom – A Review. *Frontiers in Plant Science 12*: Article 630396. https://doi.org/10.3389/fpls.2021.630396

Vega Rodríguez A, Rodríguez-Oramas C, Sanjuán Velázquez E, Hardisson de la Torre A, Rubio Armendáriz C, Carrascosa Iruzubieta C. 2022. Myths and Realities about Genetically Modified Food: A Risk-Benefit Analysis. *Applied Science 12*: Article 2861. https://doi.org/10.3390/app12062861

Voisey CR, Dudas B, Biggs R, Burgess EP, Wigley PJ, McGregor PG, Lough TJ, Beck DL, Forster RL, White DW. 2001. Transgenic pest and disease resistant white clover plants. *In*: Spangenberg, G (Editor). Molecular Breeding of Forage Crops: Proceedings of the 2nd International Symposium, Molecular Breeding of Forage Crops, Lorne and Hamilton, Victoria, Australia, November 19–24, 2000. Springer, Netherlands. Pp. 239-250.

Voisey CR, White DWR, Wigley PJ, Chilcott CN, McGregor PG, Woodfield DR. 1994. Release of transgenic white clover plants expressing *Bacillus thuringiensis* genes: An ecological perspective. *Biocontrol Science and Technology 4*: 475-481. https://doi.org/10.1080/09583159409355359

Weinhold B. 2006. Epigenetics: The science of change. *Environmental Health Perspectives 114*: Article 3 CID: https://doi.org/10.1289/ehp.114-a160

Wickson F, Binimelis R, Herrero A. 2-16. Should Organic Agriculture Maintain Its Opposition to GM? New Techniques Writing the Same Old Story. *Sustainability 8*: Article 1105. https://doi.org/10.3390/su8111105

Winichayakul S, Beechey-Gradwell Z, Muetzel S, Molano G, Crowther T, Lewis S, Xue H, Burke J, Bryan G, Roberts NJ. 2020. In vitro gas production and rumen fermentation profile of fresh and ensiled genetically modified high–metabolizable energy ryegrass. *Journal of Dairy Science 103*: 2405–2418. https://doi.org/10.3168/jds.2019-16781

Wolt JD, Wolf C. 2018. Policy and governance perspectives for regulation of genome edited crops in the United States. *Frontiers in Plant Science 9*: Article 1606. https://doi.org/10.3389/fpls.2018.01606

Xiao Z, Kerr WA. 2022. Biotechnology in China – regulation, investment, and delayed commercialization, *GM Crops and Food 13*: 86-96. https://doi.org/10.1080/21645698.2022.2068336

Xinhua 2021. China continues to receive largest share of New Zealand exports: statistics. [Accessed 26 March 2023] http://www.xinhuanet.com/english/asiapacific/2021-07/26/c_1310086422.htm