GM Crops & Food

Biotechnology in Agriculture and the Food Chain

ISSN: 2164-5698 (Print) 2164-5701 (Online) Journal homepage: https://www.tandfonline.com/loi/kgmc20

The impact of Genetically Modified (GM) crops in modern agriculture: A review

Ruchir Raman

To cite this article: Ruchir Raman (2017) The impact of Genetically Modified (GM) crops in modern agriculture: A review, GM Crops & Food, 8:4, 195-208, DOI: 10.1080/21645698.2017.1413522

To link to this article: https://doi.org/10.1080/21645698.2017.1413522

Accepted author version posted online: 13 Dec 2017.
Published online: 03 Jan 2018.

GM Crops & Food, 8:195–208, 2017

ISSN: 2164-5698 print / 2164-5701 online
DOI: 10.1080/21645698.2017.1413522

REVIEW

The impact of Genetically Modified (GM) crops in modern agriculture: A review

Ruchir Raman

Faculty of Science (School of Biosciences), The University of Melbourne, Parkville, VIC 3010, Australia

ABSTRACT. Genetic modification in plants was first recorded 10,000 years ago in Southwest Asia where humans first bred plants through artificial selection and selective breeding. Since then, advancements in agriculture science and technology have brought about the current GM crop revolution. GM crops are promising to mitigate current and future problems in commercial agriculture, with proven case studies in Indian cotton and Australian canola. However, controversial studies such as the Monarch Butterfly study (1999) and the Séralini affair (2012) along with current problems linked to insect resistance and potential health risks have jeopardised its standing with the public and policymakers, even leading to full and partial bans in certain countries. Nevertheless, the current growth rate of the GM seed market at 9.83–10% CAGR along with promising research avenues in biofortification, precise DNA integration and stress tolerance have forecast it to bring productivity and prosperity to commercial agriculture.

KEYWORDS. Genetic modification, GM, Agriculture, Crop

INTRODUCTION

Genetic modification (GM) is the area of biotechnology which concerns itself with the manipulation of the genetic material in living organisms, enabling them to perform specific functions.[1,2] The earliest concept of modification for domestication and consumption of plants dates back ∼10,000 years where human ancestors practiced “selective breeding” and “artificial selection” – the Darwinian-coined terms broadly referring to selection of parent organisms having

Correspondence to: Ruchir Raman; School of BioSciences, The University of Melbourne, Parkville Campus Victoria 3010, Australia; Email:ruchirmail@yahoo.com
Received September 5, 2017; Revised November 20, 2017; Accepted November 22, 2017.

desirable traits (eg: hardier stems) and breeding them for propagating their traits. The most dramatic alteration of plant genetics using these methods occurred through artificial selection of corn – from a weedy grass possessing tiny ears and few kernels (teosinte; earliest recorded growth: central Balsas river valley, southern Mexico 6300 years ago) to the current cultivars of edible corn and maize plants (Doebley *et al.,* 2016, Fig 1). The use of similar techniques has also been reported to derive current variants of apples, broccoli and bananas different from their ancestral plant forms which are vastly desirable for human consumption.[3]

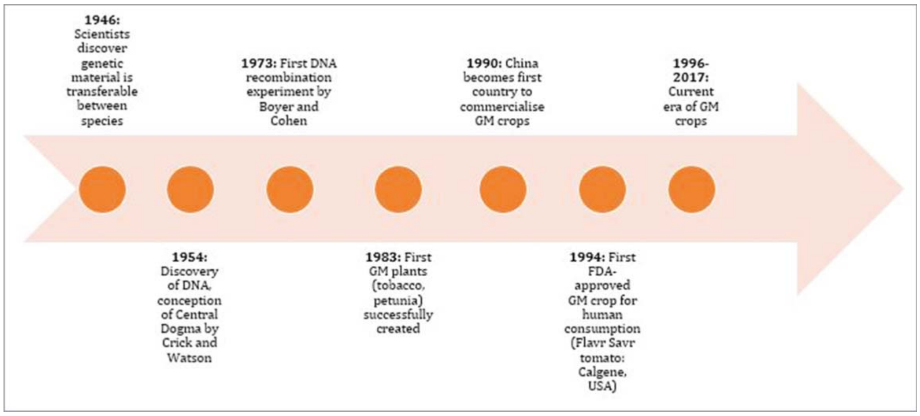
The developments leading to modern genetic modification took place in 1946 where scientists first discovered that genetic material was transferable between different species. This was followed by DNA double helical structure discovery and conception of the central dogma – the transcription of DNA to RNA and subsequent translation into proteins – by Watson and Crick in 1954. Consequently, a series of breakthrough experiments by Boyer and Cohen in 1973, which involved "cutting and pasting" DNA between different species using restriction endonucleases and DNA ligase – "molecular scissors and glue" (Rangel, 2016) successfully engineered the world's first GM organism. In agriculture, the first GM plants – antibiotic resistant tobacco and petunia – were successfully created in 1983 by three independent research groups. In 1990, China became the first country to commercialise GM tobacco for virus resistance. In 1994, the Flavr Savr tomato (Calgene, USA) became the first ever Food and Drug Administration (FDA) approved GM plant for human consumption. This tomato was genetically modified by antisense technology to interfere with polygalacturonase enzyme production, consequently causing delayed ripening and resistance to rot.[4] Since then, several transgenic crops received approvals for large scale human production in 1995 and 1996. Initial FDA-approved plants included corn/maize, cotton and potatoes (*Bacillus thuringiensis* (Bt) gene modification, Ciba-Geigy and Monsanto) canola (Calgene: increased oil production), cotton (Calgene: bromoxynil resistance) and Roundup Ready soybeans (Monsanto: glyphosate resistance),[4] Fig 2). Currently, the GM crop pipeline has expanded to cover other fruits, vegetables and cereals such as lettuce, strawberries, eggplant, sugarcane, rice, wheat, carrots etc. with planned uses to increase vaccine bioproduction, nutrients in animal feed as well as confer salinity and drought resistant traits for plant growth in unfavourable climates and environment.[4,2]

FIGURE 1. The evolution of modern corn/maize (top) from teosinte plants (bottom) by repetitive selective breeding over several generations. [Sources: [50] (top figure),[51] (bottom figure)].

Since their commercialisation, GM crops have been beneficial to both economy and the environment. The global food crop yield (1996–2013) has increased by > 370 million tonnes over a relatively small acreage area.[2] Furthermore, GM crops have been recorded to reduce environmental and ecological impacts, leading to increases in species diversity. It is therefore unsurprising that GM crops have been commended by agricultural scientists, growers and most environmentalists worldwide.

Nevertheless, advancements in GM crops have raised significant questions of their safety and efficacy. The GM seed industry has been plagued with problems related to human health and insect resistance which have seriously undermined their beneficial effects. Moreover, poor science communication by seed companies, a significant lack of safety studies and current

FIGURE 2. A timeline of events leading to the current GM crop era.



mistrust regarding GMOs have only compounded problems. These have led many countries, particularly the European Union and Middle East to implement partial or full restrictions on GM crops. GM agriculture is now widely discussed in both positive and negative frames, and currently serves as a hotbed of debate in public and policymaking levels.

CHALLENGES IN COMMERCIAL AGRICULTURE

The agriculture industry has been valued at an estimated US$ 3.2 trillion worldwide and accounts for a large share of the GDP and employment in developing and underdeveloped nations.[5] For instance: Agriculture contributes only 1.4% towards the GDP and 1.62% of the workforce in US in comparison with South Asian regions, where it contributes 18.6% towards the GDP and 50% of the workforce.[6] However, despite employing nearly 1 in 5 people worldwide (19% of the world's population),[7] the agriculture industry is projected to suffer significant global setbacks (population growth, pest resistance and burden on natural resources) by 2050, which has been elaborated further in this section.

Explosive Population Growth

The Food and Agricultural Organisation projects the global population to grow to approximately 9.7 billion by 2050 – a near 50% increase from 2013 – and further to an estimated 11bn by 2100. Current agricultural practices alone cannot sustain the world population and eradicate malnutrition and hunger on a global scale in the future. Indeed, the FAO also estimates that despite a significant reduction in global hunger, 653 mn people will still be undernourished in 2030.[8] Additionally, Ray *et al.* and other studies depict the top four global crops (soybean, maize, wheat and rice) are increasing at 1.0%, 0.9%, 1.6% and 1.3% per annum respectively– approximately 42%, 38%, 67% and 55% lower than the required growth rate (2.4%/annum) to sustain the global population in 2050.[9] Compounded with other problems such as improved nutritional standards in the burgeoning lower-middle class and projected loss in arable land (from 0.242 ha/person in 2016 to 0.18 ha/person in 2050)[2] due to degradation and accelerated urbanization, rapid world population expansion will increase demand for food resources.

Pests and Crop Diseases

Annual crop loss to pests alone account for 20–40% of the global crop losses. In terms of economic value, tackling crop diseases and epidemics and invasive insect problem costs the agriculture industry approximately $290 mn annually.[8] Currently, major epidemics continue to plague commercial agriculture. It has been projected that crop disease and pest incidences are expanding in a poleward direction (2.7 km annually),[10] indicated by coffee leaf rust and wheat rust outbreaks in Central America. These incidences have largely been attributed to an amalgamation of globalisation leading to increased plant, pest and disease movement, increase in disease vectors, climate change and global warming.[8]

While integrated pest management and prevention techniques somewhat mitigate the pest problem, they are insufficient to tackle the transboundary crop-demics. The epidemiology of the Panama disease (or Panama wilt), caused by the soil fungus *Fusarium oxysporum* f.sp. *cubense* (Foc)[11] provides solid evidence in this regard. Since the early-mid 1990s the Tropical Race-4 (TR4) strain, a single pathogen Foc fungus clone, has significantly crippled the global banana industry. In 2013, the Mindanao Banana Farmers and Exporters association (in Philippines) reported infection in 5900 hectares of bananas, including 3000 hectares that were abandoned. In Mozambique, symptomatic plants currently account for >20% of total banana plantations (570,000 out 2.5m) since the reporting of TR4 in 2015. Additionally, TR4 losses have cost Taiwanese, Malaysian, and Indonesian economies a combined estimate of US$ 388.4 mn.[12] Therefore, an alarming increase in transboundary crop and pest diseases have broad environmental, social and economic impacts on farmers and threaten food security.

Burden on Natural Resources

The FAO's 2050 projections suggest projected natural resource scarcities for crop care.[8] Despite overall agricultural efficiency, unsustainable competition has intensified due to urbanisation, population growth, industrialisation and climate change. Deforestation for agricultural purposes has driven 80% of the deforestation worldwide. In tropical and subtropical areas where deforestation is still widespread, agricultural expansion accounted for loss of 7 million hectares per annum of natural forests between 2000–2010.[8] Additionally, water withdrawals for agriculture accounted for 70% of all withdrawals, seriously depleting natural water resources in many countries. This has particularly been observed in low rainfall regions, such as Middle East, North Africa and Central Asia where water for agriculture accounts for 80–90%[8] of the total water withdrawal. These trends are predicted to continue well into the 21st century and therefore increase the burden of natural resource consumption globally.

SOLUTIONS PROVIDED BY GM CROPS

GM crops have been largely successful in mitigating the above major agriculture challenges while providing numerous benefits to growers worldwide. From 1996–2013, they generated $117.6 bn over 17 years in global farm income benefit alone. The global yearly net income increased by 34.3% in 2010–2012.[13,14] Furthermore, while increasing global yield by 22%, GM crops reduced pesticide (active ingredient) usage by 37% and environmental impact (insecticide and herbicide use) by 18%.[15] To achieve the same yield standards more than 300 million acres of conventional crops would have been needed, which would have further compounded current environmental and socioeconomic problems in agriculture.[2]

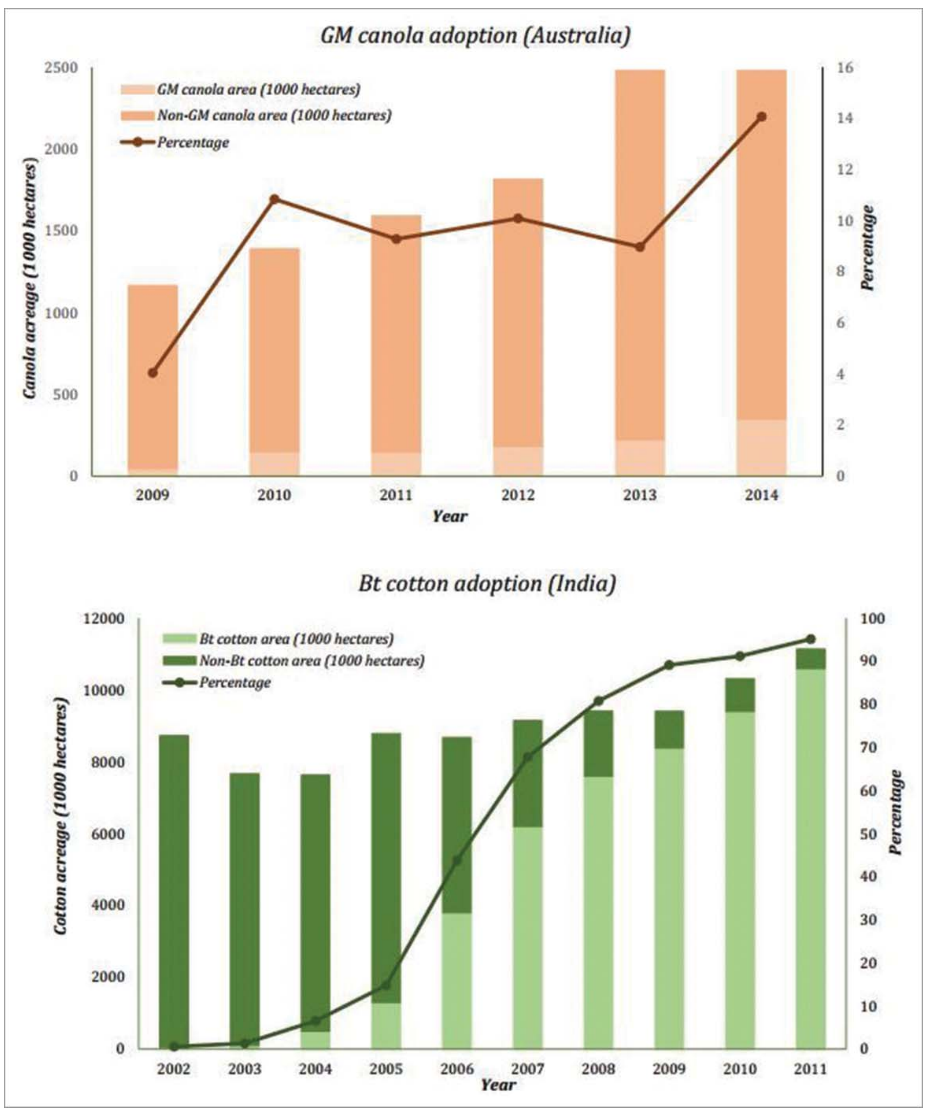
To further emphasise the impact of GM crops on economies: two case studies – GM Canola (Australia) and GM cotton (India) – have been highlighted in this review.

GM Cotton (India)

In India, cotton has served as an important fibre and textile raw material and plays a vital role in its industrial and agricultural economy. Nearly 8 million farmers, most of them small and medium (having less than 15 acres of farm size and an average of 3–4 acres of cotton holdings) depend on this crop for their livelihood. In 2002, Monsanto-Mahyco introduced Bollgard-I, India's first GM cotton hybrid containing *Cry1Ac*-producing *Bacillus thuringiensis* (*Bt*) genes for controlling the pink bollworm (*P. gossypiella*) pest.[16] Initially, only 36% of the farmers adopted the new crop however this statistic soon grew to 46% in 2004[17] after *Bt*-cotton was approved nationwide. This was followed by approval and launch of Bollgard-II (a two-toxin *Cry1Ac* and *Cry2Ab*-producing *Bt*-pyramid conferring resistance to bollworm) by Monsanto-Mahyco, which subsequently enhanced *Bt*-cotton adoption among Indian cotton growers (Fig 3).

Despite controversies, *Bt*-cotton's implementation has largely benefited Indian farmers and agricultural economy. *Bt*-cotton has increased profits and yield by Rs. 1877 per acre (US$38) and 126 kg/acre of farmland respectively, 50% and 24% more than profit and yield by conventional cotton. This translates to a net increase of

FIGURE 3. Adoption of GM canola (top) and GM cotton (bottom) in Australia and India respectively. The primary vertical axis shows the total acreage of cotton and canola along with the proportion of GM and non-GM crops grown per year, while the secondary horizontal axis depicts the percentage of GM crop adoption among farmers and growers per year. (Sources: [22,18]).



Bt-cotton growers' annual consumption expenditures by 18% (Rs. 15,841/US$321) compared to non-adapters, highlighting improved living standards.[17] *Bt*-cotton adoption has also resulted in a 22-fold increase in India's agri-biotech industry due to an unprecedented 212-fold rise in plantings from 2002–2011 (accounting for ~30% of global cotton farmland), surpassing China and making it a world leading grower and exporter. 7 million out of the 8 million farmers (88%) are growing Bt-cotton annually. Cotton crop yields have also increased 31% while conversely insecticide usage has more than halved (46% to 21%) enhancing India's cotton income by US$11.9 bn.[18] Therefore, *Bt*-cotton has resulted in economic prosperity among *Bt*-cotton growers, with 2002–11 often being called a white gold period for India's GM cotton industry.

GM Canola (Australia)

Canola in Australia is grown as a break crop, providing farmers a profitable alternative along with rotational benefits from continuous cereal crop phases and their related weed/pest mechanisms. Other benefits include broadleaf weed and cereal root disease control and better successive cereal crop growth. It is most prominently grown in Western Australia (WA), where it accounts for 400–800,000 ha of farmland and is the most successful of four break crops (oat, lupin, canola and field pea). From 2002–2007, Canola production in WA alone accounted for a yield of 440 mn tonnes valued at A$200mn.[19] Nevertheless Canola has been a high risk crop and particularly susceptible to blackleg disease (caused by fungus *Leptosphaeria maculans*), and weeds such as charlock (*Sinapis arvensis*), wild radish (*Raphanus raphanistrum* L) and Buchan (*Hirschfeldia incana* (L.) Lagr.-Foss) which increase anti-nutritional compound content and composition in canola oil, degrading quality.[20]

In 2008–09, two herbicide resistant GM canola varieties: Roundup Ready® (Monsanto) and InVigor® (Bayer Cropsciences) were introduced in Australia. Roundup Ready® contained gene variants with altered EPSP synthase (5-enolpyruvylshikimate-3-phosphate) alterations along with a glyphosate oxidoreductase gene making it glyphosate resistant. It gained OGTR approval after trials showed its environmental impact was less than half (43%) of triazine tolerant canola varieties[21,19] and remains the only OGTR-approved GM canola till date. The introduction of Roundup Ready® canola has had a positive impact on farmers by controlling weeds that were erstwhile difficult to mitigate. In 2014, GM canola planting area (hectares) was up to 14% in 2014 from just 4% in 2009 (Fig 3), representing a near three-fold increase and contributing to Australia's growing biotech crop hectarage. This increase was more notable in WA, where GM canola was planted from 21% canola farmers in 2014, up from 0% in 2009.[22] This has led to more research and development of different canola varieties to improve oil content and quality, yield and maturity.[20]

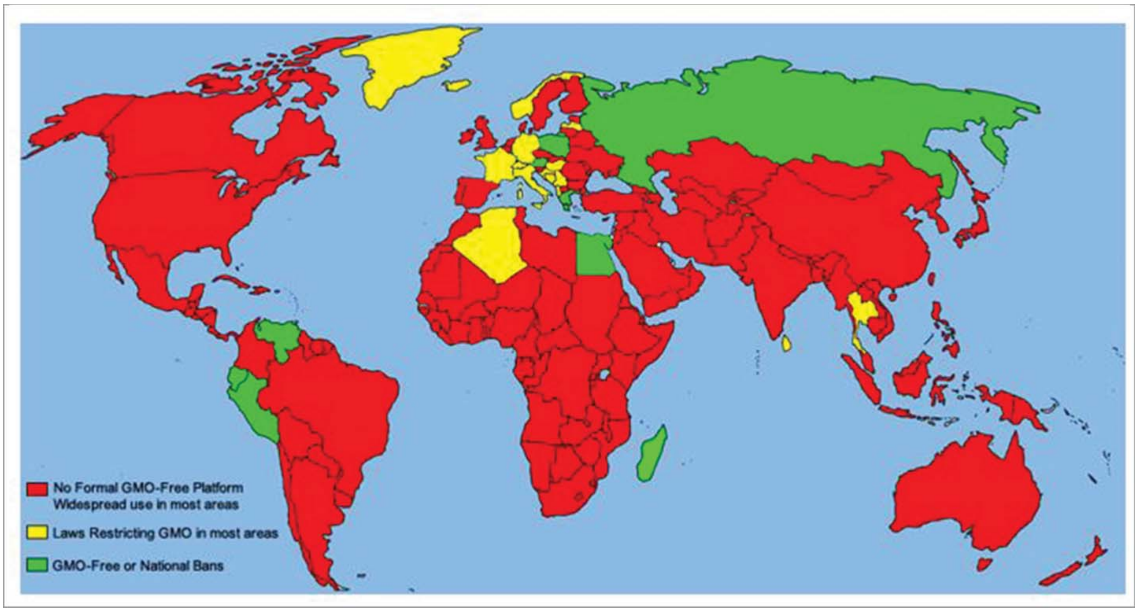
PROBLEMS AND CONTROVERSIES

Although a successful technology, GM crop use has been controversial and a hotbed for opposition. Their public image has been severely impacted leading to full or partial bans in 38 countries including the European Union (Fig 4). This section highlights major controversies and reflects on some real problems faced by commercialised GM crops.

Monarch Butterfly Controversy (1999)

The Monarch butterfly controversy relates Losey et al.'s publication in Nature wherein they compared Monarch butterfly (*Danaus plexippus*) larval feeding cycle of milkweed (*Asclepias* curassavica) dusted with N4640-*Bt* maize pollen to a control (milkweed dusted with untransformed corn pollen). They observed the N4640-*Bt* reared larvae to eat lesser, grow slower and have higher mortality and predicted N4640-*Bt* maize to have significant off target effects and significantly impact

FIGURE 4. The figure depicts the current acceptance of GM crops in different countries. Green: National bans. Yellow: Restrictive laws, Red: No formal laws (Source: [52]).



Monarch populations due to the following reasons:

- Monarch larvae's main nutrition is derived from milkweed, which commonly occurs in and around the corn field edges.
- Maize pollen shedding coincides with monarch larval feeding cycles during seasonal summer.
- ~50% of the Monarch population is concentrated within the US maize belt during summer, a region known for intense maize production.[23]

Losey *et al.*'s conclusions were challenged by academics for improper experimental design and validity and soundness of extrapolating laboratory assays to field testing. There were many subsequent studies performed, depicting *Bt*-maize to be highly unlikely to affect Monarch population. For instance: Pleasants *et al.,*[24] reasoned that several factors, most notably rainfall (reducing pollen by 54–86%) and leaf pollen distribution (30–50% on upper plant portions/preferred larval feeding sites) reduced larval exposure to *Bt*-maize pollen[24] and Sears *et al.,*[25] argued that *Bt*-maize production, should it rise to ~80% would only affect 0.05%-6% monarch population.[25]

Nevertheless, Losey *et al.*'s results garnered acclaim in the press for raising both the public's and biotech companies' consciousness about possible off-target *Bt*-maize on monarch butterflies. However further attempts to extrapolate their results to other *Bt* and GM crops have been unsuccessful, with current evidence suggesting effectiveness in insect control without off-target effects.[25]

The Séralini Affair (2012)

The Séralini affair concerns itself with a controversial GM crop study by Gilles-Éric Séralini in *Springer* during 2012–14. The original paper published in 2012 studied the effect of NK-603 Roundup Ready® Maize (NK-603 RR Maize) on rats. It used the same experimental setup as an earlier Monsanto safety study to gain maize approval[26] and reached the following observations:

- Significant chronic kidney deficiencies representing 76% of altered parameters.
- 3–5x higher incidence of necrosis and liver congestions in treated males.
- 2–3-fold increase in female treatment group mortality.
- High tumour incidences in both treated sexes, starting 600 days earlier than control (only one tumour noted in control).

The 2012 study attributed observations to EPSPS overexpression in NK-603 RR Maize, found the Monsanto study conclusions "unjustifiable" and recommended thorough long-term toxicity feeding studies on edible GM crops.[27] The paper divided opinion, with Séralini being framed as both as a hero of the anti-GM movement and as an unethical researcher. His paper drew heavy criticism for its flawed experimental design, animal type used for study, statistical analysis and data presentation deficiencies and overall misrepresentations of science and was retracted (Arjó *et al.,* 2012,.[28] In 2014, Séralini republished his nearly-identical study in expanded form which since continues to fuel the GM crop debate.

GM Crops: An Imperfect Technology

Despite the above controversies being proven unfounded, GM crops are an "imperfect technology" with potential major health risks of toxicity, allergenicity and genetic hazards associated to them. These could be caused by inserted gene products and their potential pleiotropic effects, the GMO's natural gene disruption or a combination of both factors.[4,2] The most notable example of this is Starlink maize, a *Cry9c*-expressing cultivar conferring glufosinate resistance. In the mid-1990s, the USDA's Scientific Advisory Panel (SAP) classified *Cry9c* Starlink as "potentially allergenic" due to its potential to interact with the human immune system. In 1998, the US Environment Protection Agency (EPA) granted approval for Starlink's use in commercial animal feed and industry (eg: biofuels) but banned it for human consumption. Following this, relatively small Starlink quantities (~0.5% of the US corn acreage) were planted between 1998–2000.[29,30] In 2000, Starlink residues were detected in food supplies not only in USA but also EU, Japan and South Korea where it completely banned. Furthermore, the EPA received several adverse allergic event reports related to corn, prompting a worldwide Starlink recall. About 300 different maize products were recalled in US alone by Kellogg's and Mission Foods. Starlink inadvertently affected ~50% of US maize supply and depressed US corn prices by 8% for CY2001.[31]

Another problem faced by GM crops currently is pest resistance due to gene overexpression leading to pest evolution via natural selection. Indeed, an analysis of 77 studies' results by Tabashnik *et al.* depicted reduced *Bt*-crop efficacy caused by field evolved pest resistance for 5 out of 13 (38.4%) major pest species examined in 2013, compared to just one in 2005,[32] Table 1). Furthermore, such resistance can be evolved over several generations in a relatively short time as most insects have shorter life spans. In maize, *S.frugiperda* and *B.fusca* resistance was reported after just 3 and 8 years respectively, consistent with the

TABLE 1. Crops reported with >50% pest resistance and reduced efficacy.

Pest	Affected crop	Country	Gene[2]	Time to resistance (years)[1]
B. fusca (Maize stalk borer)	Maize	South Africa	*Cry1Ab*	8
D.v.virgifera (Western Corn Rootworm)	Maize	USA	*Cry3Bb*	7
P. gossypiella (Pink Bollworm)	Cotton	India	*Cry1Ac*	6
H. zea (Corn earworm)	Cotton	USA	*Cry1Ac*	6
S. frugiperda (Fall armyworm)	Maize	USA	*Cry1F*	3

1- Time to first reported resistance of pest to GM plant. 2-Toxin secreted by affected GM plant.

worst case scenarios. In the former, it led to crop withdrawal in Puerto Rico and was reported to still affect maize growers in 2011, 4 years after crop withdrawal. In India, *P. gossypiella* resistance currently affects ~90% Bollgard-II *Bt*-hybrid cotton growers and ~35% (4 million ha) of cultivable cotton area in key regions.[32,33]

To mitigate the problems regarding GM technologies, a series of strict regulatory measures have been proposed to prevent cross-contamination of split-approved GM crops banned for human consumption. These include implementation and enforcement buffer zones to prevent cross contamination of crops, better laboratory testing to confirm adverse allergic event cases and an overall inclusion of stakeholders and representatives in policymaking and communication.[30] Additionally, *Bt* pest resistance could be controlled by implementation of high-dose *Bt* toxin standards in transgenic crops and evaluation of insect responses, integration of Host plant resistance (HPR) traits in cultivars to control secondary pests,[34] preparation of abundant non-*Bt* plants refuges near *Bt* crops and proactive implementation of two-toxin *Bt*-pyramids producing ≥ 2 distinct toxins against as single pest species.[32] These suggested measures in pest management and regulation if implemented could help the agriculture industry overcome the imperfect problems of GM crops while significantly regaining public trust of this technology.

GM AGRICULTURE: TRENDS AND FUTURE AVENUES

The GM seed market has changed drastically since 1996 from a competitive sector owned by family owners to one of the fastest growing global industries dominated by a small number of corporations. Analysts predict a Compounded Annual Growth Rate (CAGR) between 9.83–10% between 2017–2022 for this industry where it is projected to reach US$113.28 bn, an approximately four-fold increase from US$26.7 bn in 2007,[35,36] MarketWatch, 2016). This has been attributed to a rising biofuel adoption in lieu of conventional fuels in Asia-Pacific (APAC) and Africa, leading to increase plantings of energy crops (wheat, sugarcane, corn and soybean) for production. Nevertheless, despite growth spikes in APAC and Africa, North America currently dominates the GM seed industry with a market share of ~30%, and is forecast to do so in 2020 (MarketWatch, 2017).

The GM seed market has currently been consolidated by the "big five" companies: Monsanto, Bayer CropScience, Dupont, Syngenta and Groupe Limagrain (Table 2). As of 2016, they account for 70% of the market (up from ~60% in 2009).[37,38] The "big five" players are currently acquiring and forming joint ventures with smaller firms and competitors on a transnational scale, serving as strong entry barriers in this industry.[36] Since 2016, major ongoing Mergers and Acquisitions (M&As): Syngenta's takeover by ChemChina (completed June 2017- US$43 bn),[39] Bayer-Monsanto merger (ongoing- $66bn)[40] and Dow-Dupont merger (~US$140 bn- antitrust approval)[41] have been happening in the industry. Only time will determine how these M&As impact the industry, growers and consumers.

The latest reports indicate that the agriculture industry invests around $69 billion globally on its Research and Development (R&D).[42] This investment has fuelled research many emerging avenues for GM crop technology. However, innovation has strictly been influenced by the "big five" due to broad patent claims, and high research, legal and development costs for patent eligible products. For instance, the top 3 seed companies controlled 85% transgenic and 70% non-transgenic corn patents in USA in 2009.[36]

In the GM seed market, R&D is currently occurring in the conventional areas of insect resistance, increased crop yield and herbicide tolerance. Increasing R&D has also been invested on precision site-directed nuclease techniques (CRISPR, ZFNs and TALENs) for desired gene integration in host plants.[14,43] Current studies show negligible/zero off target mutations (Schnell *et al.,* 2015,.[44] This is starkly contrasting to conventional breeding techniques which are often associated with undesired alteration risks via linkage drag and

TABLE 2. A snapshot of the "big five" GM seed companies.

Company	Headquarters	Industry	Status	Product types	Financials					Website
					FY2016 Revenue (Billions US$)	FY2016 Net income (Billions US$)	Share price (2016–2017)		Market Capitalisation	
							52wk low	52wk high	(Billions) and share (%)[6]	
Monsanto	Missouri, USA	Agribusiness	Merger with Bayer AG[2]	Herbicides, pesticides, Crop seeds, GMOs	13.5	1.32	USD 97.35	USD 118.97	USD 51.41 26%	https://monsanto.com/
Dupont (Pioneer)	Delaware, USA	Agriculture/ Subsidiary of Dupont	Merger with Dow: antitrust approval (US$ 140 bn)[2]	Hybrid and Varietal Seeds	7.743	1.113	USD 66.02	USD 85.48	USD 73.23 18.2%	http://www.dupont.com
Syngenta	Basel, Switzerland	Agribusiness, Chemicals	ChemChina takeover (US$ 43bn)[2]	Pesticides, Seeds, Flowers	12.79[1]	1.181[1]	USD 74.52	USD 93.61	USD 42.56 9.2%	http://www.syngenta.com/
Groupe Limagrain	Puy-de-dome, France	Horticulture	Independent	Seeds	2.92[1, 5]	0.066[1, 5]	Not quoted[4], 4.8%			http://www.limagrain.com/?lang=en
Bayer AG (Bayer CropScience)	Leverkusen, Germany	Agriculture/ Subsidiary of Bayer AG	Merger with Monsanto2	Crop protection, pest control (non-agriculture), seeds, plant biotechnology	54.541	5.281	EUR 84.40	EUR 123.90	EUR 91.75 3.3%	https://www.bayer.com/

1 – Converted from EUR at current NASDAQ rates (July 2017), 2 – Ongoing Merger/Acquisition, 3- Completed Merger/Acquisition, 4- Public non-quoted company, 5- Sourced from Hoovers D&B, 2017, 6 – In this case, market share represents global market share and market capitalisation is local.

random, unspecified mutations.[45] Additionally, biofortification and stress tolerance have been identified as areas for future GM seed research. Both fields are currently of major interest with a growing body of scientific studies. They tackle key problems: while biofortification addresses malnutrition and micronutrient deficiency; stress tolerance addresses biodegradation, climate change and shrinking cultivable area. Since the development of Vitamin-A biofortified rice in 2000,[46] studies highlight further extrapolation in enhancing human diet using biofortifications, with recorded success in iron and zinc.[47] Moreover, recent genetic modification studies in Arabidopsis and Barley have depicted adaptation to stress tolerance and biomass growth in adverse conditions (Mendiondo *et al.,* 2016,.[48] Three stress-tolerant corn hybrids [Pioneer Optimum AQUAmax™ (Dupont Pioneer), Syngenta Artesian™ (Syngenta) and Genuity™ DroughtGard™ (Monsanto)] are currently being marketed for drought resistance,[49] showcasing enormous potential for economic profitability in the above areas.

CONCLUSION

GM crops can mitigate several current challenges in commercial agriculture. Current market trends project them as one of the fastest growing and innovative global industries, which not only benefit growers but also consumers and major country economies. However, it is imperative that the agricultural industry and science community invest in better science communication and regulation to tackle unethical research and misinformation. Imperfections and major GM technology can also be combated by stricter regulation, monitoring and implementation by government agriculture bodies, a globally improved risk mitigation strategy and communication with growers, therefore ensuring greater acceptance. With key innovation in precision gene-integration technologies and emerging research in biofortification and stress tolerance, GM crops are forecast to bring productivity and profitability in commercial agriculture for smoother progress in the future.

ACKNOWLEDGMENTS

Although this review article is my own work, it would not have been possible without certain people. I would like to thank the editor and the reviewers for their helpful comments and remarks. I would also like to extend my gratitude towards the University of Melbourne staff, especially Dr. Matthew Digby and Mrs. Fiona Simpson for their encouragement in this venture. I would further extend my thanks to my peers, teachers and other people I met during my academic journey. Lastly, I would like to extend my deepest appreciation towards my family, who encouraged me to pursue a scientific career in Biotechnology and have been wonderfully supportive of my career goals. This review article is my maiden article in an academic journal, and I would like to thank all the readers for being a part of it.

ORCID

Ruchir Raman http://orcid.org/0000-0001-8293-8198

REFERENCES

1. Morse S, Mannion AM "Genetically modified cotton and sustainability". Geographical Paper No. 184. Department of Geography School of Human and Environmental Sciences University of Reading Whiteknights, Reading, Berkshire RG6 6AB; 2008.
2. Zhang C, Wohlhueter R, Zhang H. Genetically modified foods: A critical review of their promise and problems. Food Science and Human Wellness. 2016;5(3):116–123. doi:10.1016/j.fshw.2016.04.002
3. Rangel G From Corgis to Corn: A brief look at the long history of GMO Technology – Science in the News. Harvard University: The Graduate School of Arts and Sciences; 2015. Available at: http://sitn.hms.harvard.edu/flash/2015/from-corgis-to-corn-a-brief-look-at-the-long-history-of-gmo-technology/ [Accessed 28 Jun. 2017].
4. Bawa A, Anilakumar K. Genetically modified foods: safety, risks and public concerns—a review. J Food Sci Technol. 2013;50(6):1035–1046. doi:10.1007/s13197-012-0899-1.

5. World Bank. Agriculture, value added (current US$). 2017. Available at: http://data.worldbank.org/indicator/NV.AGR.TOTL.CD [Accessed 5 Jul. 2017].
6. Nayar R, Gottret P, Mitra P, Betcherman G, Lee YM, Santos I, Dahal M, Shrestha M More and Better Jobs in South Asia. South Asia development matters. 1st ed. Washington DC: The World Bank. © World Bank; 2012.
7. CropLife International. Agriculture: A $2.4 Trillion Industry Worth Protecting. 2017. Available at: https://croplife.org/news/agriculture–a–2–4–trillion-industry-worth-protecting/ [Accessed 10 Jul. 2017].
8. FAO. The future of food and agriculture | FAO | Food and Agriculture Organization of the United Nations. 2017. Available at: http://www.fao.org/publications/fofa/en/ [Accessed 3 Jul. 2017].
9. Ray D, Mueller N, West P, Foley J. Yield Trends are insufficient to double global crop production by 2050. PLoS One. 2013;8(6):e66428. doi:10.1371/journal.pone.0066428.
10. Bebber DP, Holmes T, Gurr SJ. The global spread of crop pests and pathogens. Global Ecol Biogeogr. 2014;23(12):1398–1407. doi:10.1111/geb.12214.
11. Ordonez N, Seidl M, Waalwijk C, Drenth A, Kilian A, Thomma B, Ploetz R, Kema G. Worse comes to worst: Bananas and Panama Disease—When Plant and Pathogen clones meet. PLoS Pathog. 2015;11(11):e1005197. doi:10.1371/journal.ppat.1005197.
12. ProMusa Organisation. Tropical race 4 – TR4 | News, knowledge and information on bananas. 2017. Available at: http://www.promusa.org/Tropical+race+4+-+TR4#Impact [Accessed 11 Jul. 2017].
13. Brookes G, Barfoot P. Economic impact of GM crops: The global income and production effects 1996–2012. GM Crops Food. 2014;5(1):65–75. doi:10.4161/gmcr.28098.
14. Chen H, Lin Y. Promise and issues of genetically modified crops. Curr Opin Plant Biol. 2013;16(2):255–260. doi:10.1016/j.pbi.2013.03.007.
15. Klümper W, Qaim M. A Meta-Analysis of the impacts of genetically modified crops. PLoS One. 2014;9(11):e111629. doi:10.1371/journal.pone.0111629.
16. Choudhary B, Gaur K Biotech Cotton in India, 2002 to 2014. ISAAA Series of Biotech Crop Profiles. Ithaca, NY: ISAAA; 2015.
17. Kathage J, Qaim M. Economic impacts and impact dynamics of Bt (Bacillus thuringiensis) cotton in India. Proc Natl Acad Sci. 2012;109(29):11652–11656. doi:10.1073/pnas.1203647109.
18. James C Global status of commercialized biotech/GM crops, 2011. 43rd ed. Ithaca, N.Y.: International Service for the Acquisition of Agri-biotech Applications (ISAAA); 2011.
19. Fisher J, Tozer P Evaluation of the environmental and economic impact of Roundup Ready® canola in the Western Australia crop production system. Northam, W.A.: Curtin University of Technology Muresk, School of Agriculture and Environment; 2009.
20. Salisbury P, Cowling W, Potter T. Continuing innovation in Australian canola breeding. Crop and Pasture Science. 2016;67(4):266. doi:10.1071/CP15262.
21. Agriculture Victoria. What is Canola and GM Canola? | Genetically Modified Crops | Biotechnology | Innovation and research | Agriculture | Agriculture Victoria. 2017. Available at: http://agriculture.vic.gov.au/agriculture/innovation-and-research/biotechnology/genetically-modified-crops/what-is-canola-and-gm-canola [Accessed 25 Jun. 2017].
22. ABCA. GM canola growth in Australia (2009–2014) | Agricultural Biotechnology Council of Australia. 2017. Available at: https://www.abca.com.au/ [Accessed 5 Jul. 2017].
23. Losey J, Rayor L, Carter M. Transgenic pollen harms monarch larvae. Nature. 1999;399(6733):214–214. doi:10.1038/20338.
24. Pleasants J, Hellmich R, Dively G, Sears M, Stanley-Horn D, Mattila H, Foster J, Clark P, Jones G. Corn pollen deposition on milkweeds in and near cornfields. Proc Natl Acad Sci. 2001;98(21):11919–11924. doi:10.1073/pnas.211287498.
25. Sears M, Hellmich R, Stanley-Horn D, Oberhauser K, Pleasants J, Mattila H, Siegfried B, Dively G. Impact of Bt corn pollen on monarch butterfly populations: A risk assessment. Proc Natl Acad Sci. 2001;98(21):11937–11942. doi:10.1073/pnas.211329998.
26. Hammond B, Dudek R, Lemen J, Nemeth M. Results of a 13 week safety assurance study with rats fed grain from glyphosate tolerant corn. Food Chem Toxicol. 2004;42(6):1003–1014. doi:10.1016/j.fct.2004.02.013.
27. Séralini G, Clair E, Mesnage R, Gress S, Defarge N, Malatesta M, Hennequin D, de Vendômois J. Republished study: long-term toxicity of a Roundup herbicide and a Roundup-tolerantgenetically modified maize. Environ Sci Eur. 2014;26(14).
28. Zdziarski I, Edwards J, Carman J, Haynes J GM crops and the rat digestive tract: A critical review. Environ Int. 2014;73:423–433. doi:10.1016/j.envint.2014.08.018.
29. US EPA. Starlink™ corn regulatory information | Pesticides |US EPA. 2017. Available at: https://www3.epa.gov/pesticides/chem_search/reg_actions/pip/starlink_corn.htm#proposal [Accessed 5 Jul. 2017].
30. Bucchini L, Goldman L. Starlink Corn: A Risk analysis. Environ Health Perspect. 2002;110(1):5–13. doi:10.1289/ehp.021105.

31. Carter C, Smith A. Estimating the market effect of a food Scare: The case of genetically modified StarLink Corn. Rev Econ Stat. 2007;89(3):522–533. doi:10.1162/rest.89.3.522.
32. Tabashnik B, Brévault T, Carrière Y. Insect resistance to Bt crops: lessons from the first billion acres. Nat Biotechnol. 2013;31(6):510–521. doi:10.1038/nbt.2597.
33. Jain B. Bt cotton falling to pest, Maharashtra tensed – Times of India. The Times of India. 2017. Available at: http://timesofindia.indiatimes.com/city/mumbai/bt-cotton-falling-to-pest-maharashtra-tensed/articleshow/59449010.cms [Accessed 29 Jun. 2017].
34. Trapero C, Wilson I, Stiller W, Wilson L. Enhancing integrated pest management in GM Cotton Systems using host plant resistance. Front Plant Sci. 2016;7(1):1–12.
35. Cision: PR Newswire. Seed market Worth 113.28 Billion USD by 2022. 2016. Available at: http://www.prnewswire.com/news-releases/seed-market-worth-11328-billion-usd-by-2022-604264946.html#continue-jump [Accessed 27 Jun. 2017].
36. Howard P. Visualizing consolidation in the Global Seed Industry: 1996–2008. Sustainability. 2009;1(4):1266–1287. doi:10.3390/su1041266.
37. Business Wire. Global genetically modified seeds market to witness growth through 2020 Due to rise in adoption of Bio-fuels: Reports Technavio. 2016. Available at: http://www.businesswire.com/news/home/20160830005089/en/Global-Genetically-Modified-Seeds-Market-Witness-Growth [Accessed 27 Jun. 2017].
38. ETC Group. Who Owns Nature? Corporate power and the final frontier in the commodification of life, pp 11-16. Ottawa: ETC group; 2008
39. Fortune Finance. ChemChina clinches Its $43 Billion Takeover of Syngenta. 2017. Available at: http://fortune.com/2017/05/05/chemchina-syngenta-deal-acquisition/ [Accessed 28 Jun. 2017].
40. Tovey A. Bayer agrees $66bn Monsanto deal to create agrichemicals giant. The Telegraph. 2017. Available at: http://www.telegraph.co.uk/business/2016/09/14/bayer-agrees-66bn-monsanto-deal-to-create-agrichemicals-giant/ [Accessed 3 Jul. 2017].
41. McLaughlin D, Kaskey J. Dow-DuPont Wins U.S. Antitrust Nod to create chemicals giant. Bloomberg Markets. 2017. Available at: https://www.bloomberg.com/news/articles/2017-06-15/dow-dupont-wins-u-s-antitrust-nod-to-create-chemicals-giant-j3ytxk4y [Accessed 26 Jun. 2017].
42. Smyth S. Genetically modified crops, regulatory delays, and international trade. Food and Energy Security. 2017;6(2):78–86. doi:10.1002/fes3.100.
43. Pacher M, Puchta H. From classical mutagenesis to nuclease-based breeding – directing natural DNA repair for a natural end-product. Plant J. 2017;90(4):819–833. doi:10.1111/tpj.13469.
44. Svitashev S, Schwartz C, Lenderts B, Young J, Mark Cigan A Genome editing in maize directed by CRISPR–Cas9 ribonucleoprotein complexes. Nat Commun. 2016;7:13274. doi:10.1038/ncomms13274.
45. Liang Z, Chen K, Li T, Zhang Y, Wang Y, Zhao Q, Liu J, Zhang H, Liu C, Ran Y, Gao C. Efficient DNA-free genome editing of bread wheat using CRISPR/Cas9 ribonucleoprotein complexes. Nat Commun. 2017;8:14261. doi:10.1038/ncomms14261.
46. Beyer Y, Al-Babili S, Ye X, Lucca P, Schaub P, Welsch R, Potrykus I. Engineering the Provitamin A (-Carotene) Biosynthetic pathway into (Carotenoid-Free) Rice endosperm. Science. 2000;287(5451):303–305. doi:10.1126/science.287.5451.303.
47. Bouis H, Saltzman A. Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. Glob Food Sec. 2017;12:49–58. doi:10.1016/j.gfs.2017.01.009.
48. Sukrong S, Yun K, Stadler P, Kumar C, Facciuolo T, Moffatt B, Falcone D. Improved growth and stress tolerance in the Arabidopsis oxt1 Mutant triggered by altered adenine metabolism. Mol Plant. 2012;5(6):1310–1332. doi:10.1093/mp/sss065.
49. Adee E, Roozeboom K, Balboa G, Schlegel A, Ciampitti I. Drought-Tolerant corn hybrids Yield More in Drought-Stressed environments with No Penalty in Non-stressed Environments. Front Plant Sci. 2016;7(1534)
50. Centre for Food Safety. Proposed Oregon legislation would allow communities to protect Farmers' traditional crops from contamination by genetically engineered crops. 2016. Available at: https://www.centerforfoodsafety.org/press-releases/4211/proposed-oregon-legislation-would-allow-communities-to-protect-farmers-traditional-crops-from-contamination-by-genetically-engineered-crops [Accessed 17 Jul. 2017].
51. Singh P, Kumar S, Kumar A, Kumar R. Effect of crop establishment/irrigation techniques and nitrogen levels on growth, yield, nutrient uptake and quality of hybrid maize (Zea mays L.). International Journal of Agronomy and Agricultural Research (IJAAR). 2015;6(6):82–90.
52. Genetic Literacy Project. Where are GMOs grown and banned?. 2017. Available at: https://gmo.geneticliteracyproject.org/FAQ/where-are-gmos-grown-and-banned/ [Accessed 14 Jul. 2017].
53. Arjó G, Portero M, Piñol C, Viñas J, Matias-Guiu X, Capell T, Bartholomaeus A, Parrott W, Christou P. Plurality of opinion, scientific discourse and pseudoscience: an in depth analysis of the Séralini et al. study claiming that Roundup™ Ready corn or the herbicide Roundup™ cause cancer in rats.

Transgenic Res. 2013;22(2):255–267. doi:10.1007/s11248-013-9692-9.

54. D&B Hoovers. Groupe Liamgrain | Revenue and financial reports. 2017. Available at: http://www.hoovers.com/company-information/cs/revenue-financial.limagrain.e9663bcf85b2d99f.html [Accessed 3 Jul. 2017].
55. Doebley J, Gaut B, Smith B The Molecular genetics of crop domestication. Cell. 2006;127(7):1309–1321. doi:10.1016/j.cell.2006.12.006.
56. MarketWatch. Genetically modified seeds Market – 9.83% CAGR to 2020. 2016. Available at: http://www.marketwatch.com/story/genetically-modified-seeds-market—983-cagr-to-2020-2016-09-07-6203112 [Accessed 9 Jul. 2017].
57. Mendiondo G, Gibbs D, Szurman-Zubrzycka M, Korn A, Marquez J, Szarejko I, Maluszynski M, King J, Axcell B, Smart K, Corbineau F, Holdsworth M. Enhanced waterlogging tolerance in barley by manipulation of expression of the N-end rule pathway E3 ligase PROTEOLYSIS6. Plant Biotechnol J. 2015;14(1):40–50. doi:10.1111/pbi.12334.
58. NASDAQ. NASDAQ's Homepage for retail investors. 2017. Available at: http://www.nasdaq.com/ [Accessed 4 Jul. 2017].
59. Schnell J, Steele M, Bean J, Neuspiel M, Girard C, Dormann N, Pearson C, Savoie A, Bourbonnière L, Macdonald P. A comparative analysis of insertional effects in genetically engineered plants: considerations for pre-market assessments. Transgenic Res. 2014;24(1):1–17. doi:10.1007/s11248-014-9843-7.