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GM CROPS

GM as a route for delivery of sustainable crop protection

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Abstract

Modern agriculture, with its vast monocultures of lush fertilized crops, provides an ideal environment for adapted pests, weeds, and diseases. This vulnerability has implications for food security: when new pesticide-resistant pest biotypes evolve they can devastate crops. Even with existing crop protection measures, approximately one-third yield losses occur globally. Given the projected increase in demand for food (70% by 2050 according to the UN), sustainable ways of preventing these losses are needed. Development of resistant crop cultivars can make an important contribution. However, traditional crop breeding programmes are limited by the time taken to move resistance traits into elite crop genetic backgrounds and the limited gene pools in which to search for novel resistance. Furthermore, resistance based on single genes does not protect against the full spectrum of pests, weeds, and diseases, and is more likely to break down as pests evolve counter-resistance. Although not necessarily a panacea, GM (genetic modification) techniques greatly facilitate transfer of genes and thus provide a route to overcome these constraints. Effective resistance traits can be precisely and conveniently moved into mainstream crop cultivars. Resistance genes can be stacked to make it harder for pests to evolve counter-resistance and to provide multiple resistances to different attackers. GM-based crop protection could substantially reduce the need for farmers to apply pesticides to their crops and would make agricultural production more efficient in terms of resources used (land, energy, water). These benefits merit consideration by environmentalists willing to keep an open mind on the GM debate.

Key words: Crop improvement, GM debate, plant–pest interactions, sustainable agriculture.

Introduction

Agriculture can be defined as artificial management to enhance the food value of cultivated land. Since the earliest days of agriculture, >10 000 years ago, humankind has played an active role in promoting crop plant growth by ensuring that plants are cultivated in suitable conditions and with suitable inputs. Crops have been continuously improved, and the seed that is sown is the most important agricultural input. Modern crops have been selected over millennia and bear little resemblance to their wild ancestors. When selection is strong, domestication can drastically reduce genetic diversity in crop plant species (Wang *et al.*, 1999). The earliest farmers, although they had a very limited understanding of genetics, caused far-reaching changes in the genetic make-up of their crops simply by choosing to sow seed from the preferred plants which had the best qualities. A debt is owed to our ancestors for developing such plants which sustain modern civilization. Clearly if mankind were to return to being hunter-gatherers there would not been enough food to meet the demand of current global human population levels.

The gradual development of crop plants through artificial selection speeded up when the study of genetics allowed more scientific approaches to plant breeding to be developed. With the advent of Mendelian genetics, our understanding of the genes underpinning plant phenotypes increased and the selection of crop plants became more systematic. Gregor Mendel made fundamental discoveries by developing pure lines, counting results, and keeping meticulous notes to show that hereditary determinants are material entities (genes) (Hartl and Orel, 1992). Recently use of molecular markers and mapping of genes has greatly assisted plant breeders in their efforts (Tanksley *et al.*, 1989). However, crop improvement by conventional breeding relies on the gene pool available in a given crop, and introgression of a new trait can take a long period of time, particularly if it is sourced from more distant relatives of the elite cultivars grown commercially. Despite the use of increasingly sophisticated marker-assisted selection methods, yields in important crops, especially wheat, have not increased much in the last 10 years (Jones, 2011). Furthermore, the genetic base of staple crops currently used for human consumption is narrow, with an estimated three-quarters of calories being obtained from only four crop species: wheat, rice, maize, and soybeans (Gressel, 2008).

Crop genetic improvement methods

One approach to increase the size of the gene pool available for selection has been to expose the seed of mainstream crop cultivars to mutagenic chemicals or high levels of radiation in order to increase random mutations (reviewed by Chopra, 2005). This well-established approach, known as 'mutagenesis screening', involves generating wide-ranging genetic changes and lacks precision. However, it is a well accepted method for genetic improvement of food crops.

GM or genetic modification is the common term used to refer to insertion of genes into genomes using artificial techniques instead of natural crossing and recombination. This allows much finer control than with traditional breeding. Most crop plants possess at least 1 Gb of DNA sequence and to add a 10 kb gene results in a plant that is 99.999% identical to the one from which it is derived (Jones, 2011). New traits can be directly inserted into 'elite' crop genetic backgrounds that already possess favourable combinations of other important traits. This greatly speeds up the breeding process by eliminating the problem of 'linkage drag' which is the transfer of undesirable genes along with the gene of interest that occurs in traditional crop breeding (Gust *et al.*, 2010). Furthermore, it creates new opportunities by making a much wider gene pool available to crop breeders. So far commercial use of GM crops has been dominated by two major traits: the *Bt* endotoxin for resistance against lepidopteran insect pests, and glyphosate herbicide tolerance. These have made important contributions to increasing agricultural yields but, as with any crop protection method when overused, pests can evolve resistance. There is, thus, a need for a wider range of GM traits for crop protection to be brought into use.

Social factors and the adoption of GM crops

Public opinion of GM crops varies globally; for example, it is generally more positive in the Americas, Asia, and South Africa than in Europe. There is a cultural dimension to this which partly reflects attitudes to risk and the unknown in affluent, well-fed societies and an assumption that something new is more dangerous than something old. GM crops are sometimes portrayed in a stereotyped way by the media or by pressure groups as posing a huge threat to the environment or to health. Sections of the media previously saw 'the GM debate' as a chance to make sensationalist or even scare-mongering news stories with headlines about 'Frankenstein foods' and 'Mutant crops could kill you' (Durant and Lindsey, 2000). This very antagonistic stance has become dated, and an increasing number of people believe it is time to move on (Moore, 2010; Jones, 2011). The assumed environmental catastrophes and health disasters simply have not occurred in countries where GM crops have been grown and consumed for many years now. In fact, maize cobs derived from *Bt* maize often show reduced mycotoxin levels. This is because *Fusarium* fungi that make toxins such as fumonisin B enter through holes made by caterpillars in the cob or stem in non-GM maize (Bakan *et al.*, 2002). Thus, *Bt* maize is often safer to eat. Concerns about gene flow into wild relatives or other crops can be addressed by conducting a risk assessment and devising strategies to minimize any negative impact this may have (Daniell, 2002; Wilkinson *et al.*, 2003). In general the risks of GM crops have been vastly exaggerated in comparison with the benefits they provide.

Since around 1996, GM crops have been rapidly adopted by farmers in many parts of the world. The global area of GM crops was 148 Mha in 2010 (Peng, 2011) and the top five countries, ranked in order of production, were the USA, Brazil, Argentina, India, and Canada (James, 2010).

The intrinsic vulnerability of agriculture to pests, weeds, and diseases

Modern agricultural ecosystems, with their vast monocultures of genetically uniform crops, in many ways provide ideal conditions for adapted pests, weeds, and diseases (Bruce, 2010). There is an almost unlimited food supply of lush crop which is often fertilized and irrigated. Selection of crop plants for good taste and yield has meant that many of the resistance traits present in ancestral plants have inadvertently been bred out during the domestication process. Furthermore, because of the lack of genetic diversity and large areas covered, there is very strong selection pressure for attacking organisms to evolve to use crop plants as their hosts. A global pest outbreak in one of the major staple food crops could have very serious implications for food security.

Due to the intrinsic vulnerability of agro-ecosystems to pests (taken to include weeds and pathogens in this article) there is a need for crop protection measures. It is no coincidence that the green revolution package of improved high-yielding varieties, fertilizers, and more intensive inputs also included pesticides. The changes in agriculture that increased yields often made the crops more vulnerable to attack. Increased use of fertilizers meant crops were more nutritious to pests as well as to humans (Cisneros and Godfrey, 2001; Yardim and Edwards, 2003; Facknath and Lalljee, 2005) and increased competition with weeds (Blackshaw *et al.*, 2003). The reduction in genetic diversity by using similar crop genotypes over huge areas meant that there was also less variation in natural crop resistance traits (Gressel, 2008). Despite widespread use of pesticides, global crop losses to pests, weeds, and diseases are still very high. Estimated global losses in the period 2001–2003 are 28% for wheat, 37% for rice, 31% for maize, 40% for potatoes, 26% for soybeans, and 29% for cotton (Oerke, 2006). These losses would be doubled without the use of pesticides. Furthermore, it is uncertain whether the current situation, where pesticides provide the mainstay of crop protection, is sustainable (Fig. 1).

Agricultural pests are typically species with very short generation times and a phenomenal capacity for reproduction. This means that they can quickly evolve resistant biotypes that are not affected by a given pesticide. The number of active ingredients and modes of action registered for use as pesticides has been declining in recent years. This partly reflects the increasing legislative burden and financial costs associated with developing and registering a new pesticide. Pesticide companies increasingly look to develop new pesticides with a broad spectrum of activity so that they can control many different pest targets and thus increase the size of the market in which they can be sold. The consequence of fewer different types of pesticides being used to control agricultural pests is that the selection pressure for pests to evolve resistance increases. Also, if broad-spectrum pesticides are used, the collateral damage to populations of natural enemies of pests increases and further destabilizes the agricultural ecosystem.

GM approaches to crop breeding can greatly facilitate the introgression of novel resistance traits into elite crop cultivars. This could increase the genetic diversity of pest resistance traits and reduce the negative impact of pests on crop yields. Crucially, it would provide a means of introducing resistance traits at a faster rate than that by which the pests evolve counter-resistance. This is why GM could provide a route to sustainable crop protection. However, the strength of this approach relies on discovery of novel resistance genes to incorporate using GM techniques.

Weeds are in some ways a special case as little is known about resistance genes for weeds, but these may be discovered in the future. Current GM approaches to weed control rely on herbicide tolerance, but in the future genes for resistance against the weeds themselves, for example the *Striga* resistance genes in *Desmodium* (Khan *et al.*, 2010), could be discovered and moved into crops by GM approaches. Other allelochemical root exudates, for example hydroxamic acids (Pérez and Ormeno-Núnez, 1993), could increase crop competitiveness against other weeds. Another new direction for insect pest control is to introduce traits with a non-toxic mode of action for emission of semiochemicals that repel pests or attract their natural enemies (Beale *et al.*, 2006; Kos *et al.*, 2009).

A shared goal: sustainable and environmentally sound approaches to crop protection

Sustainable agriculture is a common goal shared by both environmentalists and GM proponents (Raymond Park *et al.*, 2011). There is common ground in that both parties are deeply concerned about the future of agriculture and food. This was highlighted recently by Professor David Baulcombe in his speech, 'Reconciling Organic Crops and Biotechnology' (UK National Farmers Union, Bledisloe Memorial Lecture, December 2010) which stated, 'Until now organic production and biotechnology have been seen as opposite…there is a third way that takes the best of both approaches. It would use GM crops, for example, that are consistent with no-till agriculture, do not require toxic insecticides, resist late blight and viruses or that have enhanced nutritional content. From a trait perspective I find it difficult to see how there can be an objection to these developments'. Perhaps it is time to think what some environmentalists may at first consider unthinkable, that is, that GM crops may provide solutions to some of the environmental impacts of agriculture. Indeed several prominent environmentalists have already decided to recognize the potential benefits of having GM crops (e.g. Ronald and Adamchak, 2008; Brand, 2009; Moore, 2010). It would be naïve to imagine that non-GM

Fig. 1. Factors influencing crop protection in an agro-ecosystem. Current trends are making the system more vulnerable to pests, weeds, and diseases, but GM could provide novel resistance traits and increase crop genetic diversity.

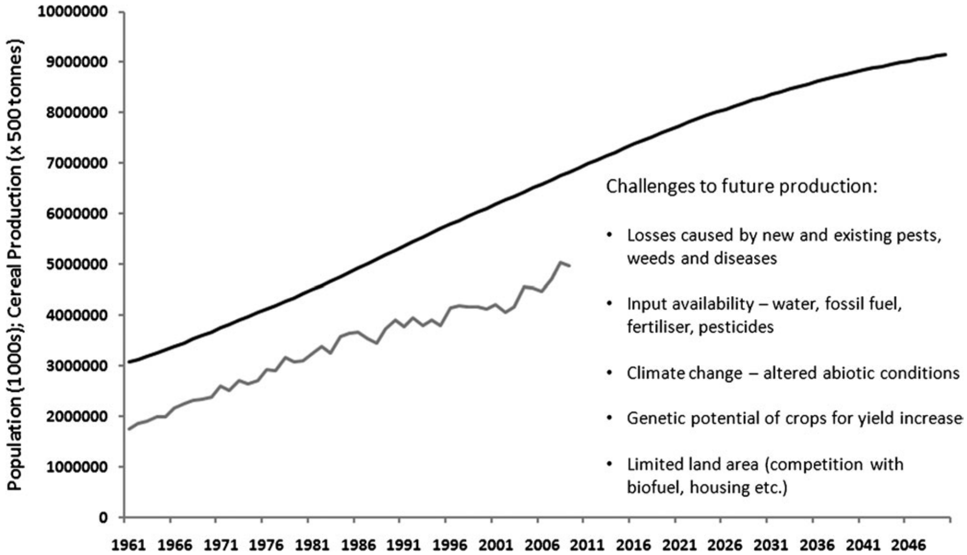

Fig. 2. Global human population growth (realized and projected) and staple cereal production (data source: FAO http://faostat.fao.org/). In the last few decades, food production has kept pace with population growth, but it is uncertain if this will continue.

crops have no harmful effects on the environment. Our current elite crop cultivars deliver high yield but rely on large inputs of fertilizer and pesticides. GM approaches could remove this dependency and actually produce crops that are more environmentally friendly. GM crops could provide advantages over conventional crops for growth under low input conditions. The focus of this article is on crop protection, but it should be noted that GM traits to increase phosphate mobilization and nitrogen use efficiency would reduce crop requirements for fertilizer and reduce the environmental footprint of agriculture.

For affluent consumers in the rich world, organic and GM-free produce are choices based on dissatisfaction with particular agricultural practices. However, for subsistence farmers in the developing world, the cost of agricultural inputs such as artificial pesticides and fertilizer is often too high and they are forced to be organic farmers. Need can change attitudes to GM, as highlighted in a recent newspaper article (*The Guardian*, 9 March 2011) where a farmer from Uganda was quoted as saying, 'Most of the people against this have choices. Somebody who is hungry does not have a choice. GM, organic or whatever—you have to feed the people.' Moreover, future projections indicate that the cost of agricultural inputs will rise with the cost of oil and that food will become more expensive as a consequence (Beddington, 2010).

The secret of sustainability is to keep as many options open for the future as possible, and to remove the GM option would limit what we can do to face the grand challenges agriculture will face in the future. These challenges are not only the evolution of pesticide-resistant biotypes but also climate change, reaching peak oil, water shortages, soil erosion, and of course the increasing demand for food as the world population continues to grow (Beddington, 2010; Godfray *et al.*, 2010) (Fig. 2). In 2008, the president of the EU stated that the food price rises had added 'a new dimension' to the public debate on GM crops. The dislike of GM is because it is perceived as unnatural. However, agriculture itself is unnatural and mutagenesis screening (described above) used in conventional breeding of crops seems more extreme than GM which introduces very precisely controlled genes.

GM crops expressing the *Bt* protein are already widely used to control Lepidopteran pests, and herbicide-tolerant GM crops have greatly facilitated weed control. Both these examples show that successful delivery of improved crop protection is possible by means of GM. For sustainable crop protection it would be better to have a greater diversity of traits increasing crop resistance to pests, weeds, and diseases (Raymond Park *et al.*, 2011). Heavy selection pressure for resistant biotypes will occur if only a limited number of traits are used. Thus, from a sustainable agriculture point of view it could be better to have more GM traits available. GM papaya that expresses a coat protein from the *Papaya ringspot virus* has saved Hawaiian papaya production which was close to being abandoned because of the disease (Stokstad, 2008). Other potentially valuable GM traits for resistance to pests, weeds, and diseases are in the pipeline (Jones, 2011; Ronald, 2011) and could deliver sustainable crop protection if farmers are allowed to use them.

Conclusions

Looking to the future, agriculture and the environment will be under enormous pressure as the world population continues to grow, water and land supplies get shorter, fossil fuel becomes more expensive, and climate change occurs (Beddington, 2010). We need to think how to increase agricultural output and minimize environmental impact. To do this, as many options as possible are needed, including the GM one which could be a very powerful tool. A second green revolution is needed. Norman Borlaug, who played a leading role in the first green revolution, has stated, 'Genetically engineered crops are playing an increasingly important role in world agriculture… I believe biotechnology will be essential to meeting future food, feed, fibre and biofuel demand' (Borlaug, 2007). The current high-yielding varieties only yield well under high input conditions, and GM will facilitate the development of crops that yield well under low input conditions, for example when pesticide use is reduced.

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References

Bakan B, Melcion D, Richard-Molard D, Cahagnier B. 2002. Fungal growth and Fusarium mycotoxin content in isogenic traditional maize and genetically modified maize grown in France and Spain. *Journal of Agricultural and Food Chemistry* **50,** 728–731.

Beale MH, Birkett MA, Bruce TJA, *et al*. 2006. Aphid alarm pheromone produced by transgenic plants affects aphid and parasitoid behavior. *Proceedings of the National Academy of Sciences, USA* **103,** 10509–10513.

Beddington J. 2010. Food security: contributions from science to a new and greener revolution. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365,** 61–71.

Blackshaw RE, Brandt RN, Janzen HH, Entz T, Grant CA, Derksen DA. 2003. Differential response of weed species to added nitrogen. *Weed Science* **51,** 532–539.

Borlaug N. 2007. Feeding a hungry world. *Science* **318,** 359.

Brand S. 2009. Whole earth discipline: an ecopragmatist manifesto. New York: Viking Penguin.

Bruce TJA. 2010. Tackling the threat to food security caused by crop pests in the new millennium. *Food Security* **2,** 133–141.

Chopra VL. 2005. Mutagenesis: investigating the process and processing the outcome for crop improvement. *Current Science* **89,** 353–359.

Cisneros JJ, Godfrey LD. 2001. Midseason pest status of the cotton aphid (Homoptera: Aphididae) in California cotton—is nitrogen a key factor? *Environmental Entomology* **30,** 501–510.

Daniell H. 2002. Molecular strategies for gene containment in transgenic crops. *Nature Biotechnology* **20,** 581–586.

Durant J, Lindsey N. 2000. The 'great GM food debate': a survey of media coverage in the first half of 1999. Parliamentary Office of Science and Technology. *Report 138*. London: House of Commons.

Facknath S, Lalljee B. 2005. Effect of soil-applied complex fertiliser on an insect–host plant relationship: *Liriomyza trifolii on Solanum tuberosum*. *Entomologia Experimentalis et Applicata* **115,** 67–77.

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C. 2010. Food security: the challenge of feeding 9 billion people. *Science* **327,** 812–818.

Gressel J. 2008. *Genetic glass ceilings: transgenics for crop biodiversity*. Baltimore, MD: John Hopkins University Press.

Gust AA, Brunner F, Nürnberger T. 2010. Biotechnological concepts for improving plant innate immunity. *Current Opinion in Biotechnology* **21,** 204–210.

Hartl DL, Orel V. 1992. What did Gregor Mendel think he discovered? *Genetics* **131,** 245–253.

James C. 2010. Global status of commercialized biotech/GM crops: 2010. *ISAAA Brief No. 42*. Ithaca, NY: ISAAA.

Jones JDG. 2011. Why genetically modified crops? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **369,** 1807–1816.

Khan ZR, Midega CAO, Bruce TJA, Hooper AM, Pickett JA. 2010. Exploiting phytochemicals for developing a 'push–pull' crop protection strategy for cereal farmers in Africa. *Journal of Experimental Botany* **61,** 4185–4196.

Kos M, van Loon JJA, Dicke M, Vet LEM. 2009. Transgenic plants as vital components of integrated pest management. *Trends in Biotechnology* **27,** 621–627.

Moore P. 2010. *Confessions of a Greenpeace dropout: the making of a sensible environmentalist*. Vancouver: Beatty Street Publishing Inc.

Oerke EC. 2006. Crop losses to pests. *Journal of Agricultural Science* **144,** 31–43.

Peng W. 2011. GM crop cultivation surges, but novel traits languish. *Nature Biotechnology* **29,** 302.

Pérez FJ, Ormeno-Núnez J. 1993. Weed growth interference from temperate cereals: the effect of a hydroxamic-acids-exuding rye (*Secale cereale* L.) cultivar. *Weed Research* **33,** 115–119.

Raymond Park J, McFarlane I, Hartley Phipps R, Ceddia G. 2011. The role of transgenic crops in sustainable development. *Plant Biotechnology Journal* **9,** 2–21.

Ronald P. 2011. Plant genetics, sustainable agriculture and global food security. *Genetics* **188,** 11–20.

Ronald PC, Adamchak RW. 2008. *Tomorrow's table—organic farming, genetics and the future of food*. New York: Oxford University Press.

Stokstad E. 2008. Papaya takes on ringspot virus and wins. *Science* **320,** 472.

Tanksley SD, Young ND, Paterson AH, Bonierbale MW. 1989. RFLP mapping in plant breeding: new tools for an old science. *Nature Biotechnology* **7,** 257–264.

Wang RL, Stec A, Hey J, Lukens L, Doebley J. 1999. The limits of selection during maize domestication. *Nature* **398,** 236–239.

Wilkinson MJ, Sweet J, Poppy GM. 2003. Risk assessment of GM plants: avoiding gridlock? *Trends in Plant Science* **8,** 208–212.

Yardım E, Edwards C. 2003. Effects of organic and synthetic fertilizer sources on pest and predatory insects associated with tomatoes. *Phytoparasitica* **31,** 324–329.