This paper is intended to convey the message of the talk I gave at the Theo Murphy meeting at the Kavli Centre in July 2010. It, like the talk, is polemical, and conveys the exasperation felt by a practitioner of genetically modified (GM) plant science at its widespread misrepresentation. I argue that sustainable intensification of agriculture, using GM as well as other technologies, reduces its environmental impact by reducing pesticide applications and conserving soil carbon by enabling low till methods. Current technologies (primarily insect resistance and herbicide tolerance) have been beneficial. Moreover, the near-term pipeline of new GM methods and traits to enhance our diet, increase crop yields and reduce losses to disease is substantial. It would be perverse to spurn this approach at a time when we need every tool in the toolbox to ensure adequate food production in the short, medium and long term.

Keywords: GM crops; insect resistance; herbicide resistance; disease resistance; food security

1. Introduction

Are genetically modified (GM) crop methods and agriculture relevant to the climate change and energy security agendas? I believe the answer is ‘Yes’ for a simple reason; we need to maximize crop yields, which GM can promote and protect. Numerous publications highlight what John Beddington has referred to as ‘the perfect storm’ facing food production. We need at least 50 per cent more food production by 2030, with little scope for additional cultivated land, with more expensive energy, with no more availability of water and the unpredictable consequences of climate change. Any farming strategy that lowers yield will require more land to produce the same amount of food, and the ploughing of uncultivated land for agriculture is one of the most environmentally damaging of human activities. The cost of energy directly impacts the cost of nitrogen fertilizer, without which yields would decline substantially. A recent Royal Society report (http://royalsociety.org/Reapingthebenefits/) addressed how science and technology could raise crop yields, and concluded that we need
both improved farming methods, better resources for training and research in the food production sector, and to use all available tools to increase the yield potential of crop varieties.

To increase yields, plant breeders select recombinant genotypes with enhanced performance in agricultural conditions. Despite progressively more sophisticated methods to measure variation in useful traits, and the advent of molecular markers to assist selection of specific genes during breeding, yields in important crops such as wheat have hardly increased in the last 10 years. Further improvements in performance by breeding can be anticipated, but it is questionable whether this will enable sufficient increases in food production. In part, this lack of improvement reflects reduced investment by the private sector in improving crops such as wheat whose seed can be saved by farmers, reducing return on breeder investment. More investment has gone into crops such as maize whose seeds are sold as F1 hybrids that must be purchased each year.

GM provides an additional technology to improve crop performance and yields, and to protect those yields from pests and diseases. GM signifies ‘genetic modification’. Of course, this term is not scientific. Darwin used the phrase ‘descent with modification’ for the process that underpins evolution, and plant breeding has created crop plants that are highly modified and visually distinct from their wild ancestors. To reserve the term GM for plants into which an extra gene has been added using Agrobacterium is to distort the meaning of the word ‘modification’. It should be noted that most crop plants carry at least 1 gigabase of DNA sequence; to add 10 kilobase of sequence results in a plant that is 99.999 per cent identical to its antecedent. Nevertheless, I will adopt common parlance and refer to GM crops.

What GM crops exist and why have farmers been happy to plant them? Farmers need to control weeds, and since hand-weeding millions of hectares is impractical, chemical herbicides are widely used. However, both weeds and crops are plants, and chemicals are required that kill the weed but not the crop. Herbicide tolerance (HT) is a major GM trait, particularly tolerance to glyphosate, usually sold under the trade name RoundUp. Glyphosate inhibits the enzyme EPSP synthase that is required for aromatic amino acid biosynthesis. The RoundUp Ready (RR) gene encodes a form of EPSP synthase that can no longer be inhibited by glyphosate. Glyphosate is not reported to have mammalian toxicity, is rapidly inactivated upon contact with soil, and is less persistent and polluting than most other herbicides. The RR gene has been widely deployed in soybeans, maize, oil seed rape (canola) and cotton. Other HT genes confer resistance to glufosinate (made by Bayer), sulfonylureas (DuPont), imidazolinones (BASF) and dicamba (2,4-D). However, like any other antibiotic, overuse of one herbicide can result in selection of resistant weed variants. Extensive use of glyphosate in soybean since 1996 has led to the appearance of ten different weed species that can tolerate RoundUp; these have become widespread and problematic in some parts of the USA. The presence of additional HT traits should address this problem. Since weed control is so important for yields, it is essential that sustainable HT strategies for weed control are implemented, in which the type of herbicide applied to a particular field is regularly rotated to prevent build-up of resistance in weed populations.
The second widely adopted GM trait has been insect resistance via engineering plants to express the *Bacillus thuringiensis* (Bt) crystal protein. This class of protein is lethal to larvae of various insects where it impairs uptake of nutrients from the gut. It has no mammalian toxicity. Different Bt proteins from various Bt strains show different specificities; one acts against corn rootworm (a Coleopteran beetle larva). Bt genes have been commercially deployed in cotton (to reduce losses to boll weevil and related Lepidopteran larvae) and maize (to reduce losses to corn borer and corn rootworm). Bacteria expressing Bt crystal protein are applied by organic farmers to control insects.

GM crops have been rapidly adopted since 1996. In UK supermarkets, a GM tomato paste developed by Zeneca sold well during 1996–1999; the GM trait slowed fruit softening and resulted in a better and cheaper paste. In 2009, 14 million farmers worldwide grew GM crops on approximately 134 million hectares, with developing country GM crop area nearly matching that in industrial countries (primarily the USA) [1]. GM continues to be rapidly adopted. RR sugarbeet achieved a 95 per cent adoption in the USA and Canada in 2009, in only its third year, making it the fastest adopted biotech globally to-date. In 2009 ‘for the first time, more than three-quarters (77%) of the 90 million hectares of soybean grown globally were biotech; for cotton, almost half (49%) of the 33 million hectares were biotech; for maize, over a quarter (26%) of the 158 million hectares grown globally were biotech; and finally for canola, 21% of the 31 million hectares were biotech’ [1].

2. GM crop outcomes

What are the consequences of this widespread adoption? According to both individual farmers and surveys, a significant environmental benefit of HT technology is reduced tillage, enabling greater carbon sequestration in RR soy fields than in non-GM soy cultivation. Another valuable benefit is reduced applications of insecticides to Bt cotton and Bt maize.

The most comprehensive analyses of benefits have come from ISAAA [1] and from PG Economics [2]. Their conclusions are broadly supported by analyses from the Royal Society and from the US National Academy of Sciences. Rather than attempt to paraphrase, I will simply quote from the ISAAA and PG Economics analyses.

‘In 2009, 5.6 million small and marginal resource-poor farmers in India planted and benefited from 8.381 (approx. 8.4) million hectares of Bt cotton, equivalent to 87% of the 9.636 (approx. 9.6) million hectare national cotton crop’ [1].

‘The deployment of Bt cotton over the last eight years has resulted in India becoming the number one exporter of cotton globally as well as the second largest cotton producer in the world. Bt cotton has literally revolutionized cotton production in India. In the short span of seven years, 2002 to 2008, Bt cotton has generated economic benefits for farmers valued at US$5.1 billion, halved insecticide requirements, contributed to the doubling of yield and transformed India from a cotton importer to a major exporter. In 2008 alone, the benefits accruing from Bt cotton in India were an impressive US$1.8 billion’ [1].
‘Progress in the first decade includes a significant reduction in pesticides, saving on fossil fuels, and decreasing CO₂ emissions through no/less ploughing, and conserving soil and moisture by optimizing the practice of no till through application of herbicide tolerance. The accumulative reduction in pesticides for the period 1996 to 2008 was estimated at 356 million kilograms (kgs) of active ingredient (a.i.), a saving of 8.4% in pesticides’ [1].

‘Of the economic gains of US$51.9 billion during the period 1996 to 2008, 49.6% were due to substantial yield gains, and 50.4% due to a reduction in production costs. In 2008, the total crop production gain globally for the 4 principal biotech crops (soybean, maize, cotton and canola) was 29.6 million metric tonnes, which would have required 10.5 million additional hectares had biotech crops not been deployed. The 29.6 million metric tonnes of increased crop production from biotech crops in 2008 comprised 17.1 million tonnes of maize, 10.1 million tonnes of soybean, 1.8 million tonnes of cotton lint and 0.6 million tonnes of canola. For the period 1996–2008 the production gain was 167.1 million tonnes, which (at 2008 average yields) would have required 62.6 million additional hectares had biotech crops not been deployed’ [1].

According to Brookes & Barfoot at PG Economics, ‘Biotech crops have contributed to significantly reducing the release of greenhouse gas emissions from agricultural practices. This results from less fuel use and additional soil carbon storage from reduced tillage with biotech crops. In 2008, this was equivalent to removing 15.6 billion kg of carbon dioxide from the atmosphere or equal to removing 6.9 million cars from the road for one year’ [2]. ‘Of the total farm income benefit, 50.5% ($26.25 billion) has been due to yield gains, with the balance arising from reductions in the cost of production. Two thirds of the yield-gain derives from adoption of insect resistant crops and the balance from herbicide tolerant crops’ [2].

An underappreciated benefit of rootworm resistant maize is that a bigger (uneaten) root system captures water and nitrogen more efficiently, and Monsanto [3] have reported improved yield under water-limiting conditions of rootworm-resistant maize. Another benefit is that maize cobs derived from Bt maize often show reduced mycotoxin levels, because *Fusarium* and *Aspergillus* fungi that make these toxins often enter through holes made by caterpillars in the cob or stem [4]. Thus, Bt maize is often safer to eat.

Plant diseases lead to substantial losses, many of which can be reduced with GM crops. By developing papaya lines that express the coat protein from papaya ringspot virus (PRV), Gonsalves *et al.* essentially saved the Hawaiian papaya industry, which was close to being abandoned due to losses from PRV [5,6].

### 3. Concerns about GM crops

Why has the adoption of this approach to solving agricultural problems and increasing the performance of crop varieties proved so unpalatable to the public? It is worth considering separately (i) why have activist groups and non-governmental organizations (NGOs) targeted the technology so vigorously? (ii) Why have the public believed the NGO propaganda?
NGOs such as Friends of the Earth, Greenpeace and the Soil Association are highly critical of multi-national corporations (MNCs) such as Monsanto acquiring excessive commercial control of the seed supply. There are legitimate concerns about monopoly control exercised by MNCs on any technology they dominate, but control of the food supply is a particularly sensitive issue, so NGO activism has touched a nerve. This anxiety has helped NGOs earn donations by campaigning against GM, encouraging continuation of their opposition. The Soil Association in particular advocates organic farming, and has stipulated that organic farmers cannot grow GM varieties; I regard its opposition to GM as ‘promoting its brand’. In the UK, it is unfortunate that the Thatcher government privatized the Plant Breeding Institute in 1988. If GM varieties had been brought forward in the UK by public sector researchers, perhaps GM would have been more acceptable to the public.

Campagners against GM cite studies from Pusztai and others that purport to show a damaging effect of a GM diet on animal health [7]. The Royal Society assessment of Pusztai’s work concluded that his inferences regarding the safety of GM food were unwarranted. There are other claims of animal ill health or reduced fertility from eating GM soy [8], none of which have provided credible grounds for disquiet; these reports have never appeared in peer-reviewed scientific literature. GM food of various kinds has been in the human food chain for over 14 years without any evidence of or grounds to suspect harm.

The emergence of RoundUp resistant weeds reminds us that when we manage an agricultural system to reduce losses to weeds, pests and disease, we impose selection on the pest population to circumvent any management tool we impose. With hindsight, it would have been better to implement earlier a rotation of the HT weed management system [9]. Farmers preferred the RR system because RoundUp is relatively cheap, and because high-performing varieties resistant to other herbicides were not available when HT technology was first deployed.

Bt technology is extremely effective against Lepidopteran larvae. However, if farmers cease to apply any insecticides at all, other insects, such as mirid bugs, can become a problem. This has happened in China [10]. We do not yet have plants that are resistant to all their potential insect pests, though we are getting closer to that as new technology becomes available. Until that time, some insecticide use is unavoidable.

Concern has been expressed that GM varieties could ‘contaminate’ other varieties. If GM were not such a sensitive issue, this would matter no more than an admixture of some existing variety with another. No GM trait or variety is authorized for agriculture without rigorous assessment of its safety, so any such admixture is not of public health concern. The seed industry is already able to ensure that poisonous high erucic acid rapeseed is not mixed with rapeseed destined to produce oil for human consumption. However, for those with deeply held beliefs that GM is bad, such admixture is seen as violating their right to avoid the technology, which imposes difficulties. What degree of intolerance from such individuals is society prepared to accept, given the cost of imposing very high standards of ‘GM freedom’, and the lack of scientific evidence that such intolerance is scientifically justified?

Could GM crops ‘escape’ and become a problem in the environment? In most agricultural landscapes, cultivated plants dominate, and it is no surprise that spillages of seed sometimes occur on roadsides, resulting in isolated populations...
of crop plants along the highway. If the crops are mostly GM, the spillages will often be GM too. However, because cultivated varieties do not compete well without fertilizer, weed control and crop protection chemicals, no such ‘escapes’ have resulted in persistent problems.

Although particular activist groups energetically campaign against GM crops, it should be noted that some campaigners with strong Green credentials are in favour of the technology. Notably, Stewart Brand, founder of the Whole Earth Catalog, in his recent book has argued that to save the planet we need GM crops for food security, and nuclear power to address pending energy shortfalls [11].

4. GM traits recently deployed or likely to be deployed in the next five years

Although most GM crop varieties to date carry HT or Bt genes, some new traits are close to deployment. This account is not exhaustive; there are simply too many traits ‘in the pipeline’ for all to be highlighted, but a selected few are mentioned below. Information about pending GM releases is available in the ISAAA documentation and at websites of the major companies, particularly Monsanto.

Seeds store phosphate in the form of inositol 6 phosphate (phytic acid). When eaten by domestic animals such as pigs and chickens, phytic acid passes through the gut unprocessed and the resulting PO₄-rich effluent promotes water eutrophication. China has approved deployment of maize that expresses the enzyme phytase in the seed, which breaks down phytic acid; after hydrolysis of phytic acid by phytase during digestion, the phosphorus is available to the animal and does not pollute watercourses [12].

China has also approved Bt rice that carries elevated resistance to rice stem borers, which cause 10–15% yield losses [1].

Monsanto released in 2010 a so-called ‘SmartStax’ maize line that carries eight different transgenes, two of which confer herbicide resistance (to glyphosate and glufosinate) and six of which are Bt genes targeted against either corn borer or root worm.

Two different genes have been developed by Monsanto and commercial partners to confer enhanced drought tolerance in maize, one of which (CspB from Bacillus) may enter commerce as soon as 2012 [13,14]. These genes are also being made available to the WEMA (water efficient maize for Africa) consortium.

Genes that offer direct consumer benefit are also becoming available. Soybean and other oilseeds accumulate significant levels of linolenic acid. To make margarine, the double bonds in these 18-carbon molecules must be hydrogenated using hydrogen and a catalyst; the resulting chemicals include partially hydrogenated ‘trans-fatty acids’ that have not previously been part of the human diet. Soy oil with reduced levels of linolenic acid produces less trans-fatty acids upon hydrogenation. Monsanto has also developed a soybean line that accumulates elevated levels of stearidonic acid in the seed; this 18:4, ω-3 fatty acid is more stable than fish oil, but is converted in the bodies of humans and domestic animals to eicosapentanoic acid or docosahexaenoic acid, long chain polyunsaturated ω-3 fatty acids that promote circulatory health.
Despite virulent opposition from NGOs, Golden Rice lines with elevated levels of beta carotene should finally become available in 2012 that can reduce the incidence of blindness and death in children resulting from inadequate levels of vitamin A [15]. Vitamin A deficiency is a serious nutritional problem, causing multiple adverse health outcomes.

In India, aubergine (also known as eggplant or brinjal) is subject to severe losses from caterpillars; insecticides are widely applied to reduce these losses. Bt brinjal resists the caterpillars and reduces the need for insecticide applications. In 2010, permission for Bt brinjal was first approved and then withdrawn, but I expect Bt brinjal to be deployed in the next 5 years.

5. Longer term challenges, opportunities and GM solutions

Again, this account cannot be exhaustive; I draw primarily from my own field of expertise of plant disease and disease resistance. It illustrates the fact that there are many small solutions (often from the public sector) to many small problems available or pending, but none of them will be deployed if the cost of regulation remains excessive.

A major disease of tomato in southern Florida is bacterial spot caused by *Xanthomonas* sp. The pepper Bs2 gene confers durable resistance to *Xanthomonas*; GM tomatoes carrying pepper Bs2 are resistant in the field to this disease [16], and efforts are underway to introduce this pepper gene into public tomato varieties for Florida. Late blight caused by *Phytophthora infestans* is a very destructive disease of potato and tomato, resulting in $6.7 billion in annual losses worldwide [17]. Several resistance genes have been cloned from wild potato relatives that confer resistance to potato late blight [18–20]. Transgenic lines show resistance in the field, though it is unlikely that any one blight resistance gene will be durable, and appropriate and varying combinations of resistance genes need to be defined. A major disease of solanaceous and other crops in the humid subtropics is bacterial wilt caused by *Ralstonia solanacearum*. An arabidopsis receptor protein, EFR, activates defence upon recognition of bacterial Ef-Tu. This recognition capacity is absent from tomato and other solanaceae. When arabidopsis EFR is introduced into tomato, the resulting lines show greatly enhanced resistance to bacterial diseases, including *R. solanacearum* [21].

Two particularly devastating diseases await durable resistance solutions. Black Sigatoka of banana caused by *Mycosphaerella fijiensis* constitutes a serious constraint on banana production; essentially all bananas consumed in the West derive from one variety (Cavendish) that is extremely susceptible. No proven GM solutions are currently available, but several promising approaches are currently being tested. A new strain of wheat stem rust caused by *Puccinia graminis*, Ug99, appeared in Africa 12 years ago. There is immense diversity in wild grasses for resistance to this strain [22,23], but introduction of these resistance genes by breeding into productive varieties is immensely time consuming and fraught with difficulty. An alternative is to directly clone these R genes from these wild relatives and introduce them into cultivated wheat using GM methods.
Tomatoes have been engineered to accumulate high levels of the antioxidants anthocyanin (‘the purple tomato’) and flavonols. Incorporation of purple tomato material into the diet of cancer-prone rats extends their lifespan [24]. This technology could be rapidly deployed, but consumer acceptance will limit when it appears on supermarket shelves.

Nitrogen fertilizer is made by the energy-intensive Haber process. Not all applied fertilizer is taken up by crops, resulting in leaching of nitrate into water-courses and the risk of eutrophication. It would be desirable to elevate the efficiency of uptake by crops and an alanine aminotransferase gene shows promise for conferring improved nitrogen use efficiency [25]. Longer term, it would be highly desirable for the capacity to establish a symbiosis with nitrogen-fixing Rhizobium bacteria to be extended from leguminous plants to others [26].

Other solutions to problems require more research before they can be deployed, but will necessarily involve use of GM methods for their application. Plants have been engineered for more efficient photosynthesis [27,28], but crops with enhanced photosynthesis derived from these technologies have yet to be demonstrated in the field.

6. Conclusion and overview

GM is a method to introduce new genes that can improve crop performance. In the last 14 years, both GM HT and insect resistance have been enthusiastically adopted by farmers in the USA, Argentina, Brazil, India and China. The outcomes have broadly been positive; easier weed control, better insect control with reduced insecticide applications, increased carbon sequestration by low till agriculture, and increased farm incomes. However, activists in Europe have greatly retarded adoption of GM, and the public has been misled by unwarranted criticisms of the technology from its opponents. This is unhelpful at a time when we need to use all available technology to secure food supplies over the next 20–40 years.

Europeans should consider the following questions about GM. First, why is so little consideration given to the costs of not using GM? For example, in the UK alone, farmers spend approximately £50 million per year to control late blight, and a 10 year delay in solving the problem thus costs £500 million. The major beneficiaries from any such delay are the fungicide manufacturers such as Bayer and Syngenta, and the major losers are consumers. Second, European politicians generally support the desirability of strengthening the European bioeconomy, but how are we to compete successfully with the USA when our regulatory burden is so much more severe? Companies such as Monsanto are the major beneficiaries from excessive and expensive regulation; it increases the barriers to entry from competitors, and maintains their monopoly position. Third, EU taxpayers spend considerable sums both nationally and Europe-wide on plant science and technology that could result via GM in EU crops with better performance and reduced environmental impact. However, excessive regulation is preventing EU taxpayers from benefitting from their own investment—why? Finally, EU regulations on import of GM crops are influencing policies in developing countries and retarding the deployment of solutions to problems of food availability and quality. How can the harm that results from these European anti-GM prejudices be justified?
I thank the Gatsby Charitable Foundation and various funding agencies for supporting my work at the Sainsbury Laboratory on plant disease and disease resistance. I declare an affiliation with Mendel Biotechnology (www.mendelbio.com), which I co-founded in 1997, and which has commercial relationships with Bayer, Monsanto and BP.

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