Food and Energy Security
Open Access

REVIEW

Food security: intensification of agriculture is essential, for which current tools must be defended and new sustainable technologies invented

John A. Pickett

Rothamsted Research, Harpenden, Hertfordshire, AL5 2JQ, United Kingdom

Keywords
Genetic modification (GM), land-sharing, pesticides, registration, safety.

Correspondence
John A. Pickett, Rothamsted Research, Harpenden, Hertfordshire, AL5 2JQ, United Kingdom. Tel: +44 0 1582 763133; Fax: +44 0 1582 762595; E-mail: john.pickett@rothamsted.ac.uk

Funding Information
Rothamsted Research receives grant-aided support from the Biotechnology and Biological Sciences Research Council (BBSRC) of the United Kingdom.

Received: 1 August 2013; Revised: 7 August 2013; Accepted: 14 August 2013

***Food and Energy Security* 2013; 2(3): 167–173**

doi: 10.1002/fes3.32

Abstract

To spare land for amenity use and to preserve natural habitats, including those for ecosystem services, food production must be intensified on land which is presently farmed. Current tools, such as pesticides, although largely unsustainable in that they require seasonal application, must be defended against the growth of legislated restrictions being imposed without recourse to scientific evidence. This is the only practical short-term approach to increasing food production without taking more land for agriculture, but more sustainable approaches delivered via the seed must be invented, including by genetic modification (GM), in order to replace seasonal inputs in the future. Eventually, perennial arable crops will be needed, thereby replacing seasonal land preparation, but, for full benefits to be realized, all crop protection and nutrition will need to be delivered via the planting material. Governments, and particularly those in the EU, must embrace risk analysis in which advantages, as well as potential hazards, are accommodated. The precautionary principle is not an appropriate approach to the registration of new technologies for achieving food security in a world suffering both climate change and rapid population increase.

Introduction

The tools of the green revolution have well served those regions where they have been adopted and developed for food production. However, in spite of tremendous efforts involving enormous international aid programs, they have not been taken up in some regions by small-scale farmers. This is particularly true for sub-Saharan Africa, where the bulk of the population comprises such farmers. Regions with more developed agriculture must continue to use and improve current technologies. This requires further development of all the inputs that maintain or have potential to raise yields, that is, fertilizers, breeding (including first generation genetic modification [GM]), and pesticides for the control of pests, diseases, and weeds. The latter are particularly important because they protect yields for which the carbon footprint of the crop is already committed (Gilbert 2012; Vermeulen et al. 2012). Nonetheless, even with these inputs, agricultural yields are currently stagnating (Cassman 1999; Brown 2005). With this overall plan, a further problem is increasing and involves public attitudes fueled by activities of lobbying organizations and elements of the mass media, together with, for some regions (particularly parts of the EU), irresponsible governmental pressure on registration agencies, all of which contribute to overburdensome restrictions on the use of many currently available tools and, if left unchecked, will seriously aggravate problems of food production in the future (European Commission 2003; European Commission, Environment, Reach 2006). Of course, use of all inputs must be regulated and directed by decision support, which is already the case for the most advanced agricultural regions and must be adopted by all those regions using these technologies. The overall attitude underpinning attacks on current inputs overlooks their value in food production, in spite of well made arguments (Peplow 2013), and uses past problems, or those arising even from criminal misuse, for example, of pesticides, and fear of the future, for example, GM, to curtail development and use in food production. For the immediate future, this is of particular concern with pesticides for which we do not yet have effective alternatives, and for GM in the longer term where it will be needed to create new traits for nutrition and pest control delivered via planting material. Education and public engagement with these issues is essential but this needs to be underpinned with scientific evidence, and all who seek to press their worries or prejudices toward legislation will need to become sufficiently knowledgeable to weigh the scientific evidence against their concerns. This is particularly true for politicians from certain regions. The overall move toward sustainable intensification will need to be focused and not diverted by issues that will rapidly become less relevant, such as organic farming and bioenergy. Food will be the priority and dramatic rises in prices will force out inefficient approaches, already clearly apparent for organic farming (Seufert et al. 2012). The food processing and marketing industries will also decline in relative power against food production, as will their opportunistic support for opposition to GM and policies reflecting their lack of direct support for research and development relative to that of the food production industries. Nonetheless, while defending current technologies, we must invent new ones and this will go far beyond the mere beginnings we have seen for GM. Indeed, much of the future needs in terms of education and research are laid out in a report by a working party convened by the Royal Society (2009), but the demand for drastically more spending is by no means being met globally, with parts of the EU embarrassingly negligent in this regard.

What is Wrong with Pesticides?

Nothing, except that pests develop resistance to these agents and their deployment is not sustainable if the pesticides are used as seasonal, or more frequent, inputs and require mechanical application. The already overcautious registration requirements ensure that currently registered, and thereby legally used, pesticides have virtually no, or certainly negligible, impact on the environment and nontarget organisms, including ourselves. Sadly, the fears of those without sufficient knowledge to make critical judgments are aggravated by peer-reviewed publications. In this, the scientific community has itself to blame. Finally, funding agencies, perhaps with some agitation from scientists showing insufficient excellence to obtain normal peer-reviewed funding, respond to public or, more correctly, political pressure to have scientific initiatives that will look at the problem. Funding then goes to those having interests in the area, with peer critique weakened also by this being in a restricted area. The ensuing studies, often with extremely poor experimental design and without a scientifically convened hypothesis, then produce results which convince some that the perceived problem is confirmed. There are many examples seeking to offer evidence that legally used pesticides could pose a problem and many more that still cite pesticides long since removed from legal use. The perceived problems range widely, from causing cancers, interfering with hormone regulation and generally damaging beneficial organisms in the environment. These gain credence even from citations criticizing them, so this will be adopted minimally here. With all these areas, references can be found using simple computer-based information searches and, with the current fashion for blaming the apparent population decline of honey and other bees on insecticides, even the scientific magazines and associated press comments oblige. Thus, rather than objectively looking for any causes, which has nonetheless been comprehensively considered by some excellent reviews (Vanbergen and the Insect Pollinators Initiative 2013), insecticides are suspected of killing bees and investigated for doing so. Indeed, insecticides seldom have such selective activity that they would not, at some level, kill or give debilitating effects at sublethal doses. The registration of pesticides, being disproportionately expensive mostly as a consequence of unnecessary testing on higher animals in attempts to satisfy unevidenced concerns, forces development toward relatively broad-spectrum effects, certainly broad enough to catch the main insect control markets, and so bee toxicity is inevitable at some level. This often forms the basis for “proving” the problem, but the most dangerous are those studies appearing to be well conducted and funded through peer review. These usually involve testing at the maximum possible levels or at higher levels than there is evidence for occurring (see comments: Cresswell and Thompson 2012; Stokstad 2013). As soon as symptoms are detected under these circumstances, evidence of a problem is then claimed. In fact, before the insecticides were registered, and specifically for all recently registered compounds such as the neonicotinoids, including imidacloprid, environmental assessments were made to ensure that there would be no problems arising from agricultural use. Therefore, the emerging extrapolations, while suggesting that there may be an interaction, fail to take into account that, even if there was, the very few dead or debilitated bees would not be a problem and not responsible for the apparent bee decline (Dicks 2013). We are now faced, after such scientific papers and much lobbying, with a potentially disastrous ban on neonicotinoid insecticides in the EU (Erickson 2013; Howes 2013; Trager 2013). Nonetheless, unperturbed, there will be responses to this article, no doubt offering a further extrapolative argument that the observed effects could combine with other phenomena, or the often used suggestion that levels of certain compounds, lower than those even for sublethal effects, can combine unexpectedly to form a lethal, or at least damaging mixture. This is, of course, possible. However, we need evidence and there are more retractions of publications than those standing which purport to show this effect.

The real issue is, where would we be without pesticides? Many more people starving than the one billion quoted at the moment, and rising, would be caused by the impact of losing at least 30% of food to pests, diseases, and weeds (Oerke 2006). Breeding has done well but traditionally looks to very narrow genetic variation, which mostly fails to produce powerful and robust resistance traits. The most dramatic successes, for example, crops expressing *Bacillus thuringiensis* (Bt) endotoxin-related genetics, involve GM to bring in traits distant from the elite crops themselves. Other alternatives, particularly involving biological controls or agro-ecological solutions, seldom work effectively. However, where appropriate tools, for example, the delivery of semiochemicals by companion crops, can be used to empower conservation biological control (Hassanali et al. 2008) and effective weed management (Pickett et al. 2010), there is considerable promise (Khan et al. 2010). There is a growing trend from some funders and developers for promoting agro-ecological approaches that has convinced many public and political observers that we could replace pesticides immediately, without loss of food production. We cannot do this presently (Bale et al. 2008) and it is irresponsible for awards and prizes to be made, with great public acclaim, that this or that pest problem is solved by this new variety or that agro-ecological approach, without rigorous scientific review. In some circles and with some funding agencies, there is an accompanying departure from peer review in favor of other, less quantifiable, measures of impact, which further aggravates the naïve belief that we have an option to obviate pesticide use. Although, in the past, state sector research has provided new inventions, for example, the synthetic pyrethroids at Rothamsted Research by Michael Elliott and his team, most discovery is in industry. Tens of thousands of compounds need to be screened even while using the most sophisticated approaches to exploiting structure–activity relationships. Unlike drug design for human or veterinary use, with pesticides, in vitro activity is sacrificed to enable delivery for field or farm application to the target site. Also, toxicological issues are more stringent for pesticides than for pharmaceuticals because of registration issues. This all argues for industrial development, with many academic attempts to enter the area involving naïve views regarding rational design and what might constitute a valuable lead compound, particularly the case for the multitude of claims for natural products in this context.

Resistance to pesticides by selection of target site or metabolic modifications is a major issue and the industry, legislators and aid agencies need scientific support in avoiding deployment that aggravates this very real problem. Long term use of highly persistent treatments can be promoted or solutions to selection pressure for resistance offered for which there is no proof of efficacy, and often the opposite. This is the case, for example, where use of mixtures, an often proposed solution, even of pesticides with different modes of action or routes to metabolism, could aggravate the problem by selecting for multiple resistance mechanisms, even though to some this is counterintuitive. Use of refugia, intended to allow maintenance or reestablishment of susceptibility, requires sophisticated management. All of these highly demanding aspects of pesticide resistance management require resources that are being diverted to satisfy the perceived or ill-informed requirements for less pesticide impact. Not only are fewer new pesticides (Bielza et al. 2008) becoming available, but perfectly registrable compounds are being lost (Leadbeater 2011) because, once no longer covered by patents, there is less opportunity for the cost of re-registration, a feature of current registration requirements, being recovered. This will mean that small legislative regions, such as some EU countries and even the EU itself, could face loss of essential pesticides merely because they represent a small market, not justifying the high expense of registering a particular pesticide in the region. Considering only the hazard and not the likelihood of interaction, that is, risk, plus ignoring the value in food production, is an insidious danger.

What is Right with GM?

GM of the organisms involved now and in future food production represents use of a rapidly growing technology. How it is used is not a problem of the technology, nor can it be of any generic set of methods. However, to transfer genetic code from one organism to another, to change this code in organisms and even to build new organisms is of immense potential value. In spite of most of the world subscribing to a relatively free market economy, meaning that technology is transferred in some degree by private enterprise, those that violently and illegally seek to prevent, and those that offer tacit support for prevention of, developments in GM promote its commercialization by large multinational industries, because the excessive security that such activities require will detract from state sector activities in this area. This is a pity, because it may be that local needs for planting material in the future, as determined by decision support systems tuned to smaller scale regional conditions, might benefit from the inclusion of more small-to-medium business enterprises and farmer cooperatives. Nonetheless, to enable GM to impact widely on sustainable increases in food production, there will need to be a massive mobilization, not only of state funding but also from the revenue of rapidly increasing food prices into this aspect of science and development. The work must target creation of new solutions and opportunities, and should not lead to yet another round of investigations into potential but unlikely environmental and human impacts. Risk-based registration will take care of this issue but it is now time, and according to the Royal Society report (Royal Society 2009) well over time, to spend the effort on invention rather than on irrelevant aspects of safety. It is often written, and may be true, that GM is just one of the technologies for creating sustainable food production, but already it can be seen to be extremely powerful. Perhaps Bt and Roundup Ready crops do not demonstrate the impressive advantage of GM to those not close to the subject. However, we now see the clear environmental value of Bt crops (Lu et al. 2012) and the EU has changed its policy to allow importation of Brazilian Roundup Ready soya bean, because insufficient non-GM can be purchased on the world market for EU animal feed consumption (EFSA 2012). We must still demonstrate the claimed advantages and we have made rash claims in the past. Nevertheless, the very fact that we now have the prospect of producing a fish oil, having even higher levels of long chain ω-3-polyunsaturated fatty acids than cod liver oil, in an oilseed crop (Ruiz-Lopez et al. 2013), potentially as an alternative to a dwindling natural resource, and an insect pheromone in wheat (Pickett et al. in press), potentially as a means of controlling an insect pest by using genetic code from well beyond the crop plants themselves, a task impossible by breeding, demonstrates the enormous potential of these techniques. This is not to suggest that breeding itself is not moving forward to wider crosses and, reduced linkage drag (Harper et al. 2011), but using a gene sequence, even from another kingdom, is only feasible at present by GM (Jones 2011; Pérez-Massot et al. 2013), a spectacular achievement that must offer immense value in the quest for novel crop traits. New opportunities, in terms of technology developments, are proceeding rapidly, specifically with various techniques for genome engineering (Curtin et al. 2012; Li et al. 2012; Gaj et al. 2013).

So what further shall we do with GM? Clearly, plant nutrition is the ultimate target. For nitrogen, this involves the highly energy intensive Haber–Bosch process, not to mention soil preparation and delivery of other inputs. It is not yet clear exactly where this will go. However, for replacement of fossil fuel-based energy, with no longer a real prospect of bioenergy except from the waste products of food production most likely restricted to on-farm use, we must undoubtedly turn to nuclear fusion technologies and this requires massive research funding. The same level of input will be needed for solving the issue of nitrogen fixation within the crop. Already, for higher use of nitrogen fertilizers, as well as for companion cropping with nitrogen fixing legumes, we see the need for lowering the emission of the powerful greenhouse gas nitrous oxide (N_2O). Here, we could look to a more predictable solution, such as the creation of GM crops that release suitably allelopathic compounds into the rhizosphere, known for some savannah grassland plants (Subbarao et al. 2009). In all the examples so far, starting with the bacterium *B. thuringiensis* from a flour mill in Thuringia, Germany, the idea of exploiting genetic codes from species diversity is providing a compelling reason for preserving species diversity, which is often an ambition of those calling for less productive agriculture. Indeed, the idea, embodied in "sharing" land rather than "sparing" land by intensification of production, has already lost ground to hard evidence (Phalan et al. 2011; Hulme et al. 2013). However, we must ensure that such "spared" land is really used to promote, or at least to conserve, biodiversity (Hulme et al. 2013). It may be that, with GM, we could create new diversity in the interests of ecosystem services, even a bee that deals better with those traits that can cause its decline, once we have dispelled the myth that it is pesticides doing this. For enhancing food value, we have the potential example above but we must be careful to select, as has been done for the oilseed improvements, targets for which there is evidence of value. Targeting unevidenced health fads and unproven nutraceuticals would be a most decadent use of GM, and yet one that the food industry and natural product-based health businesses seem happy to embrace. For crop protection, although we may not need GM to exploit resistance traits from wide crosses, for example, with ancestor species in the form of alien introgression (Harper et al. 2011), we will need GM to bring in traits from genetic material further away and from other kingdoms. To date, we have mostly been modest in what we have done but, like the example of GM wheat producing the aphid alarm pheromone, we can now seek to exploit secondary plant metabolism further. The robustness of modern pesticides, at least in part, derives from their nature as small lipophilic molecules (SLMs) and many had natural product lead compounds exploited for their development. This is not only true of the synthetic pyrethroids (Tessier 1984), but also of some newer pesticides. For example, the insecticide spinosad is directly obtained from a natural organism, that is, the fermenter cultured *Saccharopolyspora spinosa* (Miles and Dutton 2000). Natural products have no properties superior to synthetic other than their diversity of structure (Rouhi 2003), that is, as opposed to the lack of diversity in combinatorial chemical libraries, and their existence in nature. It is the latter that allows potential exploitation via GM. However, perhaps in designing new GM targets based on these ideas, again as with GM wheat producing the aphid alarm pheromone, we should consider more sophisticated modes of action for, and SLM targets involving, disease and weed development and animal pest behavior, which include pheromones and other signaling molecules, for example, semiochemicals. Plants are themselves using such SLMs and, as these can act as elicitors of defence, they can potentially be valuable as defence elicitors and used to "switch on" defence genes in GM crops. *cis*-Jasmone, which is known to signal differently from the main jasmonate pathway, has been identified (Birkett et al. 2000; Bruce et al. 2008) as a useful defence elicitor and is under practical development for a range of crops, even without GM, but thereby demonstrating the potential. Defence elicitors like *cis*-jasmone are produced by plants, including some crops such as potato, when attacked by pests and diseases. Thus, the associated promoter sequence suitably linked to marker genes, for example, for the anthocyanin pathway, the spectral characteristics of which can be detected at a distance, could then provide new sentinel technologies needed to develop decision support systems. We have such a program involving new elicitors associated with the development of *Phakopsora pachyrizi*, the causative organism for soya bean rust, funded in a collaboration between Embrapa, Brazil, and the United Kingdom, BBSRC (UK-Brazil partnership, BB/J02029X/1). Semiochemicals can be more generic than pheromones in their range of activities, and a group of stress-related SLMs released by many plants attracting beneficial insects, particularly parasitic wasps, at the same time as repelling herbivorous pests, are isoprenoid compounds comprising one carbon more than the conventional hydrocarbons, termed "homoterpenes." These have been targeted for biodiversity studies and for use of the identified genes in GM rice crop protection in programs funded by, respectively, the BBSRC International Partnering Award BB/J02028/1 and the BBSRC China UK Programme in Global Priorities BB/L001683/1. A novel elicitor system for homoterpene induced production is being identified from studies with African colleagues at the International Centre of Insect Physiology and Ecology (*icipe*). It is released by the eggs of lepidopteran cereal pests into intact plant tissue and acts systemically within the crop plant (Tamiru et al. 2011). Release of homoterpenes by companion crops in Africa is already valuable to tens of thousands of farmers, demonstrating the potential value of capturing this trait by GM (Khan et al. 2010; Tamiru et al. 2011).

Perennialization of arable crop plants is a goal for achieving sustainable agriculture (Glover and Reganold 2010), although harvesting will still require an external input (Royal Society 2009), hence the studies introducing perenniality from perennial relatives, for example, for rice from *Oryza longistaminata* and for wheat from *Thinopyrum* species (Lammer et al. 2003; Sacks et al. 2003; Cox et al. 2006). Perennial crops will have considerably greater ecological apparency (Feeny 1976) and the highly valuable extensive root systems, a feature of perennial crops, will need to be protected from soil pests by new approaches (Sobhy et al. in press). Newly discovered rhizosphere interactions (Babikova et al. 2013) will also be exploited in managing pests via plant-to-plant signaling. Nitrogen nutrition and crop protection will need to be delivered via the planting material (see above). Pesticides will be maintained, but more for emergency pest management. In the move away from constitutive gene expression, a feature of current GM, crop plants will need to detect pest, disease or weed competition and respond by upregulation of defence genes for appropriate SLM production. A sentinel plant might offer more flexible alternatives in which, instead of "switching on" markers, for example, color for long range detection, the response to externally released signals such as *cis*-jasmone could be engineered to "switch on" defence related genes in the main crop. Such sentinel plants could also "switch on" genetics related to nutritional aspects and allow responses to benefits, for example, rain after drought, in a more dramatic way than wild-type plants. The great investment in the rhizosphere, and particularly plant roots, will engender new pest problems, and rhizosphere interactions must be studied qualitatively to produce new intervention by GM in the agricultural ecosystem. Indeed, such approaches are already emerging (Rasmann et al. 2005; Babikova et al. 2013).

Conclusions

Food production in the future will look very different, as will the overall business system. As well as the continual growth of decision support, many new regionalized business opportunities will emerge. The prestige of farming will be much higher and its new highly trained technical staff will be relatively more numerous to deal with a more information based industry with fewer but higher value inputs, though not in terms of carbon footprint. Completely new science, particularly relating to the perennial crops, will need to be conceived (Glover and Reganold 2010). This will take place in a world that will have a closer and much wider experience of serious food shortages (assuming we do not heed fully, as we have not done so far, the recommendations of the Royal Society [2009]), when it will be realized that people without sufficient food of their choice are not much in need of electronic gadgetry, nonessential pharmaceutical remedies and, of course, the extremes of incompetent banking. With regard to emerging technologies such as GM, by embracing the precautionary principle, parts of the EU risk losing out to the rest of the world, as we would have done in the past,had science not been rescued from the Inquisition in southern Europe by the growth of the Protestant ethic in the North.

Acknowledgments

Rothamsted Research receives grant-aided support from the Biotechnology and Biological Sciences Research Council (BBSRC) of the United Kingdom. I am also extremely grateful for advice and requirements brought to bear in the peer reviewing process.

Conflict of Interest

None declared.

References

Babikova, Z., L. Gilbert, T. J. A. Bruce, M. Birkett, J. C. Caulfield, C. M. Woodcock, et al. 2013. Underground signals carried through common mycelial networks warn neighbouring plants of aphid attack. Ecol. Lett. 16:835–843. doi: 10.1111/ele.12115.

Bale, J. S., J. C. van Lenteren, and F. Bigler. 2008. Biological control and sustainable food production. Philos. Trans. R. Soc. B 363:761–776. doi: 10.1098/rstb.2007.2182.

Bielza, P., I. Denholm, P. Ioannidis, G. Sterk, A. Leadbeater, P. Leonard, et al. 2008. Declaration of Ljubljana: the impact of a declining European pesticide portfolio on resistance management. Outlooks Pest Manage. 19:246–248.

Birkett, M. A., C. A. M. Campbell, K. Chamberlain, E. Guerrieri, A. J. Hick, J. L. Martin, et al. 2000. New roles for *cis*-jasmone as an insect semiochemical and in plant defense. Proc. Natl. Acad. Sci. USA 97:9329–9334.

Brown, L. R. 2005. Raising the Earth's productivity. Pp. 59–79 *in* L. Sharpe, ed. Outgrowing the Earth: the food security challenge in an age of falling water tables and rising temperatures. W. W. Norton & Co. Earth Policy Institute, New York.

Bruce, T. J. A., M. C. Matthes, K. Chamberlain, C. M. Woodcock, A. Mohib, B. Webster, et al. 2008. *cis*-Jasmone induces *Arabidopsis* genes that affect the chemical ecology of multitrophic interactions with aphids and their parasitoids. Proc. Natl. Acad. Sci. USA 105:4553–4558.

Cassman, K. G. 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA 96:5952–5959.

Cox, T. S., J. D. Glover, D. L. van Tassel, C. M. Cox, and L. R. DeHaan. 2006. Prospects for developing perennial grain crops. Bioscience 56:649–659.

Cresswell, J. E., and H. M. Thompson. 2012. Comment on "A common pesticide decreases foraging success and survival in honey bees. Science 337:1453. doi: 10.1126/science.1224618.

Curtin, S. J., D. F. Voytas, and R. M. Stupar. 2012. Genome engineering of crops with designer nucleases. Plant Genome 5:42–50.

Dicks, L. 2013. Bees, lies and evidence-based policy. Nature 494:283. doi: 10.1038/494283a.

EFSA. 2012. EFSA Panel on Genetically Modified Organisms (GMO). Scientific opinion on an application (EFSA-GMO-NL-2005-24) for the placing on the market of the herbicide tolerant genetically modified soybean 40-3-2 for cultivation under regulation (EC) No 1829/2003 from Monsanto. EFSA J. 10:2753. doi: 10.2903/j.efsa.2012.2753. Available at http://www.efsa.europa.eu/efsajournal (accessed 13 June 2013).

Erickson, B. 2013. P. 11 *in* Europe bans three neonicotinoids linked to honeybee population declines. C&EN, 6 May 2013.

European Commission. 1829/2003. European Commission DG Health and Consumers, EU Register of authorized GMOs. Available at http://ec.europa.eu/food/dyna/gm_register/index_en.cfm (accessed 15 June 2013).

European Commission, Environment, Reach. EC 1907/2006. European Community Regulation on chemicals and their safe use, EC 1907/2006. Available at http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm (accessed 15 June 2013).

Feeny, P. 1976. Plant apparency and chemical defense, in "Biochemical Interactions between Plants and Insects". Recent Adv. Phytochem. 10:1–40.

Gaj, T., C. A. Gersbach, and C. F. Barbas III. 2013. ZFN, TALEN, and CRISPR/Cas-based methods for genome engineering. Trends Biotechnol. 31:397–405. Available at http://dx.doi.org/10.1016/j.tibtech.2013.04.004 (accessed 13 June 2013).

Gilbert, N. 2012. One-third of our greenhouse gas emissions come from agriculture. Nature. News, 31 October 2012. doi: 10.1038/nature.2012.11708.

Glover, J. D., and J. P. Reganold. 2010. Perennial grains food security for the future. Issues in Science and Technology Online, Winter 2010. Available at http://www.issues.org/26.2/glover.html (accessed 13 June 2013).

Harper, J., I. Armstead, A. Thomas, C. James, D. Gasior, M. Bisaga, et al. 2011. Alien introgression in the grasses *Lolium perenne* (perennial ryegrass) and *Festuca pratensis* (meadow fescue): the development of seven monosomic substitution lines and their molecular and cytological characterization. Ann. Bot. 107:1313–1321.

Hassanali, A., H. Herren, Z. R. Khan, J. A. Pickett, and C. M. Woodcock. 2008. Integrated pest management: the push-pull approach for controlling insect pests and weeds of cereals, and its potential for other agricultural systems including animal husbandry. Philos. Trans. R. Soc. B 363:611–621.

Howes, L. 2013. P. 8 *in* Europe bans neonicotinoids. Chemistry World, June 2013.

Hulme, M. F., J. A. Vickery, R. E. Green, B. Phalan, D. E. Chamberlain, D. E. Pomeroy, et al. 2013. Conserving the birds of Uganda's banana-coffee arc: land sparing and land sharing compared. PLoS ONE 8:e54597.

Jones, J. D. 2011. Why genetically modified crops? Philos. Trans. R. Soc. A 369:1806–1816. doi: 10.1098/rsta.2010.0345.

Khan, Z. R., C. A. O. Midega, T. J. A. Bruce, A. M. Hooper, and J. A. Pickett. 2010. Exploiting phytochemicals for developing a 'push-pull' crop protection strategy for cereal farmers in Africa. J. Exp. Bot. 61:4185–4196.

Lammer, D., X. W. Cal, H. Li, M. Arterburn, J. Chatelain, A. Greco, et al. 2003. Utilization of *Thinopyrum* spp. in breeding winter wheat for disease resistance, stress tolerance, and perennial habit. Proceedings of the First Central Asian Wheat Conference *in* A. Morgounov, A. McNab, K. G. Campbell, R. Paroda, eds. Increasing wheat production in Central Asia through science and international cooperation. Almaty, Kazakhstan, 10–13 June 2003.

Leadbeater, A. 2011. The impact of the new European regulations on the management of crop diseases. Pp. 1–10 *in* H. W. Dehne, H. B. Deising, U. Gisi, K. H. Kuck, P. E. Russell and H. Lyr, eds. Modern fungicides and antifungal compounds VI. Deutsche Phytomedizinische Gesellchaft, Braunschweig, Germany.

Li, T., B. Liu, M. H. Spalding, D. P. Weeks, and B. Yang. 2012. High-efficiency TALEN-based gene editing produces disease-resistant rice. Nat. Biotechnol. 30:390–392.

Lu, Y., K. Wu, Y. Jiang, Y. Guo, and N. Desneux. 2012. Widespread adoption of Bt cotton and insecticide decrease promotes biocontrol services. Nature 487:362–365. doi: 10. 1038/nature11153.

Miles, M., and R. Dutton. 2000. Pp. 339–344 *in* Proc. Br. Crop Prot. Conf. – Pests Dis., 13–16 November 2000. Spinosad – a naturally derived insect control agent with potential for use in integrated pest management systems in greenhouses. Vol. 1. Brighton, U.K.

Oerke, E.-C. 2006. Centenary review: crop losses to pests. J. Agric. Sci. 144:31–43.

Peplow, M. 2013. Pesticide bee buzz needs more evidence. Chemistry World, 11 April, Available at http://www.rsc.org/chemistryworld/2013/04/neonicotinoid-pesticide-bee-decline-colony-collapse (accessed 13 June 2013).

Pérez-Massot, E., R. Banakar, S. Gómez-Galera, U. Zorrilla-López, G. Sanahuja, G. Arjó, et al. 2013. The contribution of transgenic plants to better health through improved nutrition: opportunities and constraints. Genes Nutr. 8:29–41. doi: 10.1007/s12263-012-0315-5.

Phalan, B., M. Onial, A. Balmford, and R. E. Green. 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333: 1289–1291.

Pickett, J. A., M. L. Hamilton, A. M. Hooper, Z. R. Khan, and C. A. O. Midega. 2010. Companion cropping to manage parasitic plants. Annu. Rev. Phytopathol. 48:161–177.

Pickett, J. A., G. Aradotttir, M. A. Birkett, T. J. A. Bruce, A. M. Hooper, C. A. O. Midega, et al. In press. Delivering sustainable crop protection systems via the seed: exploiting natural constitutive and inducible defence pathways. Philos. Trans. R. Soc. B.

Rasmann, S., T. G. Köllner, J. Degenhardt, I. Hiltpold, S. Toepfer, U. Kuhlmann, et al. 2005. Recruitment of entomopathogenic nematodes by insect-damaged maize roots. Nature 434:732–737.

Rouhi, A. M. 2003. Rediscovering natural products. Chem. Eng. News 81:77–91.

Royal Society. 2009. P. 72 *in* Reaping the benefits: science and the sustainable intensification of global agriculture. RS Policy document 11/09. Available at http://royalsociety.org/Reapingthebenefits/ (accessed 13 June 2013).

Ruiz-Lopez, N., R. P. Haslam, S. L. Usher, J. A. Napier, and O. Sayanova. 2013. Reconstitution of EPA and DHA biosynthesis in Arabidopsis: iterative metabolic engineering for the synthesis of n-3 LC-PUFAs in transgenic plants. Metab. Eng. 17C:30–41. doi: 10.1016/j.ymben.2013.03.001.

Sacks, E. J., J. P. Roxas, and M. T. Sta. Cruz. 2003. Developing perennial upland rice II: field performance of S_1 families from an intermated *Oryza sativa*/*O. longistaminata* population. Crop Sci. 43:129–134.

Seufert, V., N. Ramankutty, and J. A. Foley. 2012. Comparing the yields of organic and conventional agriculture. Nature 485:229–232. doi: 10.1038/nature11069.

Sobhy, I. S., M. Erb, Y. Lou, and T. Turlings. In press. The prospect of applying chemical elicitors and plant strengtheners to enhance the biological control of crop pests. Philos. Trans. R. Soc. B.

Stokstad, E. 2013. Pesticides under fire for risks to pollinators. Science 340:674–676.

Subbarao, G. V., K. Nakahara, M. P. Hurtado, H. Ono, D. E. Moreta, A. F. Salcedo, et al. 2009. Evidence for biological nitrification inhibition in Brachiaria pastures. Proc. Natl. Acad. Sci. USA 106:17302–17307.

Tamiru, A., T. Bruce, C. Woodcock, J. Caulfield, C. Midega, C. Ogol, et al. 2011. Maize landraces recruit egg and larval parasitoids in response to egg deposition by a herbivore. Ecol. Lett. 14:1075–1083.

Tessier, J. 1984. Evolution of an industrial process: deltamethrin synthesis. J. Chem. Ind (Lond). 1984:199–204.

Trager, R. 2013. P. 8 *in* Europe bans neonicotinoids while the US takes a different tack on honeybee health. Chemistry World, June 2013.

Vanbergen, A. J., and the Insect Pollinators Initiative. 2013. Threats to an ecosystem service: pressures on pollinators. Front. Ecol. Environ. 11:251–259. Available at http://dx.doi.org/10.1890/120126 (accessed 13 June 2013).

Vermeulen, S. J., B. M. Campbell, and J. S. I. Ingram. 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37:195–222.

