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Review

Transgenic cereals: Current status and future prospects

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A R T I C L E I N F O

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A B S T R A C T

This review summarises the history of transgenic (GM) cereals, principally maize, and then focuses on the scientific literature published in the last two years. It describes the production of GM cereals with modified traits, divided into input traits and output traits. The first category includes herbicide tolerance and insect resistance, and resistance to abiotic and biotic stresses; the second includes altered grains for starch, protein or nutrient quality, the use of cereals for the production of high value medical or other products, and the generation of plants with improved efficiency of biofuel production. Using data from field trial and patent databases the review considers the diversity of GM lines being tested for possible future development. It also summarises the dichotomy of response to GM products in various countries, describes the basis for the varied public acceptability of such products, and assesses the development of novel breeding techniques in the light of current GM regulatory procedures.

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1. Background

On a global basis the cereals wheat, maize, rice, barley and sorghum are grown on almost 700 million hectares and collectively they provide approximately 40% of the energy and protein components of the human diet (Table 1). They therefore represent a vital contribution to food security both at present and also in the future when population growth (Dunwell, 2013) and other social and economic trends will require an approximate doubling of food production by 2050. Specific retrospective and prospective data for wheat yields, based on information from the Wheat initiative (www.wheatinitiative.org) are given in Table 2. In the words of the G20 Agriculture vice-ministers and deputies report from 2012 “Increasing production and productivity on a sustainable basis in economic, social and environmental terms, while considering the diversity of agricultural conditions, is one of the most important challenges that the world faces today” (http://www.g20.org/en). The UK Secretary of State for the Department for the Environment, Food and Rural Affairs made a major speech on 20th June 2013 about the role of GM in the future of agriculture (https://www.gov.uk/government/speeches/rt-hon-owen-paterson-mp-speech-to-rothamsted-research), and the European Academies Science Advisory Council has recently published a detailed report on the opportunities of using GM technologies in sustainable agriculture (EASAC, 2013).

Against the background of this need for increased agricultural production, this review will consider the history of genetically modified (GM) or transgenic cereals during the 30 year period since the production of the first GM plants in 1983, before discussing their present status and future potential. Information has been obtained not only from recent scientific literature but also from analysis of regulatory databases for GM crops, and from the patent literature.

2. Methods for production of GM plants

The original method devised for the production of the first GM plants in 1983 depended on the use of the natural bacterial vector *Agrobacterium tumefaciens*. At that time it was assumed that this system could not be applied to cereal species and the emphasis for these crops was focussed on direct gene transfer methods, particularly the “gene-gun” or Biolistics technology. This technology was the first method successfully applied to maize. Since that time, significant improvements have been made to the *Agrobacterium* techniques, and these techniques can now also be applied to cereals. Data for wheat, barley and oats are summarised in Dunwell (2008) and a recent summary of a diverse range of GM techniques is available in Dunwell and Wetten (2012).

These novel technologies include new methods for the design of constructs (Coussens et al., 2012; Karimi et al., 2013), that is the DNA sequences to be introduced and improved methods for DNA delivery. These latter methods include techniques for maize (Kirienko et al., 2012), wheat (Tamás-Nyitrai et al., 2012), rice (Duan et al., 2012b; Wakasa et al., 2012), barley (Harwood, 2012; Holme

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Table 1
Global area, production, yield and contribution to the human diet for major cereal crops.

	2010 (FAOSTAT)					2009 (FAOSTAT)			
	Area		Production		Yield	Energy		Protein	
	Mha	%	MT	%	Tonnes/ha	kcal/ Capita/d	%	g/ Capita/d	%
Wheat	217	32	651	27	3.0	532	18.8	16.2	20.4
Maize	162	24	844	35	5.2	141	5.0	3.4	2.3
Rice	154	23	672	28	4.4	536	18.9	10.1	12.7
Barley	48	7	123	5	2.6	7	0.2	0.2	0.3
Sorghum	41	6	56	2	1.4	32	1.1	1.0	1.3
Total	683	100	2432	100	3.6	1248	44	30.9	38.6

Adapted from Wheat Initiative (2013).

et al., 2012a), triticale (Ziemienowicz et al., 2012), and tef (*Eragrostis tef*) (Gebre et al., 2013). There is also an improved understanding of the process of regeneration from plant cells in culture (Delporte et al., 2012), an important aspect of any system for high efficiency transformation.

Temporal and spatial stability of transgene expression, as well as well-defined transgene incorporation are additional features to be considered (Bregitzer and Brown, 2013; Kim and An, 2012). Likewise, it is of practical importance that GM lines can be rapidly identified, both in the laboratory (Chen et al., 2012b; Han et al., 2013b; Hensel et al., 2012; Mieog et al., 2013; Xu et al., 2013a) and under field conditions.

Another objective in many GM research projects is the development of more efficient methods for the introduction of multiple genes. These include the construction of mini-chromosomes in rice (Xu et al., 2012a). Additionally, there has been significant progress with efforts to induce site-specific gene integration (Nandy and Srivastava, 2012; Kapusi et al., 2012) and to use GM techniques to suppress selected genes or gene families (Wang et al., 2013b). Some of these techniques are also associated with the new techniques described below in Section 5.3.

Immediately following the description of GM plants of tobacco in 1983, the commercial focus became the development of GM maize (Mumm, 2013), as this crop was already hybrid and annual sales of such high-value seed was an established part of the agricultural economy of the USA and elsewhere. In contrast, the other important cereals wheat and rice are self-pollinating crops and the value of seed sales is comparatively low, and any GM variety could in theory, if not in practice, be saved by the farmer for growth in subsequent years. For this reason, there have been several attempts to convert inbreeding species into hybrid crops either through the use of chemical hybridizing agents or via GM technology. One GM approach to the production of male sterility, a necessary component of any hybrid system (Feng et al., 2013), has recently been exemplified in wheat by expressing a barnase gene (Kempe et al., 2013).

In the summaries below, the specific traits incorporated into GM varieties will be divided into those that provide advantages to the farmer/grower, the so-called input traits and those that modify the characteristics of the harvested product, the so-called output traits.

Table 2
Evolution of wheat yield over 10-year periods since 1960 (FAO) and projected needs for 2050

Period	Mean area harvested/ yr (Mha)	Mean production/ yr (Mt)	Mean production increase/yr (%)	Mean yield (t/ha)	Mean yield increase/ yr (%)
1961–1970	213	278		1.3	
1971–1980	225	388	3.9	1.7	3.2
1981–1990	229	509	3.1	2.2	2.9
1991–2000	220	571	1.2	2.6	1.7
2001–2010	216	622	0.9	2.9	1.1
2050 (target)	220	1045	1.7	4.75	1.6

Adapted from Wheat Initiative (2013).

3. Input traits

3.1. Herbicide tolerance

Prior to GM technology herbicides were classified into two categories, either selective, those that killed weeds and not crops, and non-selective, those that killed all plants. The development of selective herbicides, in particular, is a very difficult research challenge that requires an understanding of biochemical targets found only in weeds. Transgenic technology opened the possibility of converting non-selective compounds into selective ones, if a gene conferring resistance could be identified, isolated and then transferred into the crop of interest. The most obvious candidate for this strategy was glyphosate, a widely used selective herbicide marketed by Monsanto. Eventually, a bacterial resistance gene was identified and Monsanto subsequently acquired this technology, the means of introducing this gene into maize, and a company which owned elite maize inbred lines, the target for this technique. This company then had the significant commercial advantage of being able to sell both GM herbicide-tolerant (HT) varieties, and the herbicide in question. This combined approach became highly successful and provided the blueprint for many subsequent commercial programmes in maize and other crops. The second major herbicide resistant trait was that conferring tolerance to glufosinate. The commercial need for companies to be able to market both the herbicide and HT crops containing the gene conferring tolerance led to many conflicts associated with intellectual property rights (IPR) and many mergers and acquisitions. The process of consolidation of IPR began in earnest in August 1996 with AgrEvo's purchase of Plant Genetic Systems (PGS) for $730 million, made when PGS's prior market capitalization was $30 million. According to AgrEvo, $700 million of the purchase price was assigned to the valuation of the patent-protected trait technologies (i.e., glufosinate resistance gene) owned by PGS (Pila, 2009). In all such cases it is important to avoid any yield drag associated with the presence of the transgene (Darmency, 2013).

At present most hybrid maize sold in the USA is resistant to one or more herbicides. The availability of such HT crops has provided the farmer with a variety of flexible options for weed control (Brookes and Barfoot, 2013a), despite some problems caused by the development of HT weeds, an issue that has stimulated the development of improved versions of glyphosate resistance genes and also of novel genes encoding resistance to other herbicides such as 2,4-D. In some regions, particularly in sub-Saharan Africa, HT maize has also provided a novel control strategy for hemi-parasitic weeds such as *Striga* (Ransom et al., 2012).

One novel finding in the area of HT crops is that showing the resistance of melatonin-rich GM rice plants to herbicide-induced oxidative stress (Park et al., 2013).

Monsanto also developed a glyphosate tolerant (Roundup Ready™) version of wheat, and carried out successful field tests in the 1990s. Due to concerns about international trade of GM wheat, this project was suspended in 2005, although recently in April 2013 some HT wheat plants carrying the Monsanto CP4 gene for glyphosate tolerance have been discovered growing in a farm in Oregon; their origin is uncertain (Fox, 2013; Ledford, 2013).

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