Assessing the potential economic benefits to farmers from various GM crops becoming available in the European Union by 2025: results from an expert survey

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1. Introduction

Evidence is being presented in many quarters that genetically modified (GM) crops have delivered net benefits for farmers, both small and large scale, and consumers, in the countries where cultivation has been permitted (e.g. Brookes & Barfoot, 2016 and James, 2014). Depending on the crop and trait, these benefits might be agronomic, economic and/or environmental in nature, resulting from yield improvements, better management of pests and diseases, reduced input use and nutritional improvements. While there are a growing number of commercially-grown GM crops in the world, only one GM crop is currently permitted for cultivation in the European Union (EU) i.e. Bt maize. While Bt maize cultivation occurred in five EU countries in 2014, the areas cultivated were very small, with only Spain and Portugal producing more than a few thousand hectares i.e. 131,537 ha (MAGRAMA, 2014) and 8,542 ha (Ministry of Agriculture and Sea of Portugal, 2014) respectively. As the House of Commons (2015) points out, the fact that there is only one GM crop approved for cultivation is largely due to the extremely slow and cumbersome EU GM approvals process, which requires majority member state approval in the European Council, resulting in an effective moratorium on further authorisations in the EU. As a consequence of this extremely arid policy environment, private sector investment in GM technology has moved out of the EU and consequently there is very little research being undertaken specifically focused on the needs of EU agriculture or consumers. It is, therefore, unsurprising to note that some commercial biotech companies have started to withdraw pending applications for EU authorisations for GM technologies that they have developed (EC, 2016a).

However, this 'informal' moratorium on GM authorisations within the EU might soon be lifted, as a consequence of recent changes to legislation. Directive (EU) 2015/412 of the European Parliament and of the Council of 11 March 2015, amending Directive 2001/18/EC, provides the means for the Member States to restrict or prohibit, on certain grounds, the cultivation of genetically modified organisms (GMOs) in their territory, even when these have been judged by the EU's regulators to pose no risk to human health or the environment (European Parliament and Council, 2015). Allowing Member States to unilaterally ban GM cultivation may not sound like much of a breakthrough for GM authorizations, but the rationale for allowing Member States to 'opt out' of GM cultivation in this way, is that they will not need to block agreement on GM authorisations within the European Council to maintain their own GM-free status, thereby making EU-level authorisations easier to obtain.

Outside of the EU, the development pipeline continues to produce new commercialized GM crops. The USDA Animal and Plant Health Inspection Service (APHIS), which regularly publishes lists of successful petitions for unregulated release of GM events into the environment in the USA, announced in September 2015 that the 117th such petition, for a potato with blight-resistance (Pathogen Tolerant - PT) and other properties, was approved for trials (APHIS, 2015). While there has been no incentive for commercial biotech companies to develop crop-trait combinations targeted at agronomic conditions prevailing in Europe, Stein and Rodriguez-Cerezo (2009) have noted that some GM crops already commercialized outside the EU, or within the development pipeline, are both agronomically suitable and may offer potential benefits for farmers or consumers in the EU. With a potential unblocking of the EU GM crop authorisation process now a distinct possibility, leading to some countries in the EU (such as an independent post-Brexit UK) considering adoption of GM crops, it is timely to review the GM crop-trait combinations that were currently, or soon to be available, to identify their suitability for cultivation in the EU and examine the nature of the benefits that they might offer to either farmers and/or consumers.

Almost all past evaluations of the benefits offered by potential uptake of GM technologies in the EU have focussed on the farm-scale economic benefits offered by the most common GM crops (soybean, maize, cotton and canola) and traits (herbicide tolerance [HT] and insect resistance [IR] (Kathage et al., 2016). This concentration on crop-trait combinations already commercialised (see, for example, Demont and Tollens, 2004; Demont et al., 2007; Brookes, 2007; Demont et al., 2008; Dillen et al., 2009; Carpenter, 2010) has occurred for the practical reason that these cases provide some data on the benefits obtained from adoption available from non-EU settings, or at least from field-scale trials. As Kathage et al. (2016) pointed out, the availability of data remains the primary constraint to evaluation of the impacts of GM crops in the EU setting. An exception to this trend is Flannery et al. (2004) who included some 'hypothetical' crop-trait combinations in a benefits evaluation for Ireland. For the study detailed here, it was concluded that because the policy and regulatory changes required to 'open up' EU member states to GM crop production was likely to take a number of years, the scope of this analysis could not be confined to GM technologies already commercialised, but must also have to take into account crop-trait combinations still in development, that are likely to be available in the near future, say by 2025.

The novel approach taken in the evaluation presented here i.e. extending the scope of the analysis to include GM crops not yet commercialised, presented an obvious methodological problem: that of obtaining data on the likely benefits from uptake of crops where no observational data were available. Past approaches to estimate likely benefits from GM crops grown in the EU have involved extensive surveys of non-EU production thus providing data for transfer into the EU context. When such approaches were not possible i.e. where only limited data were available, modelling exercises have been undertaken (see, for example, Demont and Tollens, 2004), sometimes involving statistical approaches, such as stochastic simulation techniques to overcome concerns about the accuracy or representativeness of the data. However, for most crops considered here, because they are yet to be commercialised, no data are available at all. To overcome this problem, we adopted the only remaining approach that could supply credible benefits data – stakeholder consultation, where a panel of experts in GM technologies provided estimates of likely future benefits of GM adoption. This approach was also applied to crop-trait combinations that are commercialised outside of the EU, as these individuals have the appropriate knowledge to make necessary adjustments to non-EU data to account for differences in agronomic conditions between the data donor and recipient countries. Stakeholder consultation seemed to provide a consistent data generation process for all cases i.e. for technologies already developed and those still in the development pipeline whether for input or output traits. The approach:

- could be informed by any economic evaluation that exists;
- could make adjustments to non-EU data to account for EU agronomic conditions; and
- could generate new ‘notional’ data where no observational data currently existed.

To maximise the quality of the data derived from the survey of stakeholders, the study employed the so-called ‘Delphi’ technique, developed at the RAND Corporation (Dalkey and Helmer, 1963). The Delphi technique takes information from a panel of well-informed individuals and builds these data into a consensus about possible future change or developments (Hsu and Sandford, 2007; Linstone and Turoff, 1975; Martino, 1993; Young and Jamieson, 2001). The key characteristic of the Delphi process is that data gathering is an iterative process, punctuated by feedback of the group results to all contributing individuals. In light of this feedback individuals are then permitted to amend their judgements until an acceptable measure of consensus is reached. Multiple iterations are sometimes required to derive an acceptable level of consensus. Data can be collected in a group setting, or anonymously, as this is an effective way of reducing the biasing effects of dominant individuals operating in group settings such as focus groups (Dalkey, 1972; Scott, 2011).

The Delphi technique has become a well-accepted means of using expert opinion to help anticipate future events in many technological, social and political fields. It has also been used to explore a diverse range of issues in the realm of food and agriculture, for example: policy forecasting (Fearne, 1986); anticipating biotechnology trends (Menrad *et al,* 1999); food supply chain developments (Ilbery *et al*, 2004); scoping the role of agriculture in flood management (Kenyon *et al,* 2008); analysis of the drivers of past Common Agricultural Policy (CAP) reform rounds (Cunha and Swinbank, 2009); examining sustainable upland rural estate management (Glass *et al*, 2013); prioritisation of management strategies to control zoonotic diseases (Stebler *et al*, 2015); and evaluation of vegetation management strategies under electric power lines (Dupras *et al*, 2016).

In this paper, we report the results of a global Delphi survey consultation into the potential agronomic and economic benefits that 12 prospective GM crop-trait combinations might offer to EU farmers and/or consumers. In addition, the paper also addresses the question of the significance of any estimated benefits identified i.e. asking the question ‘how much difference would these benefits make to the competitiveness of adopters compared to non-adopters?' Past experience suggests that once these technologies are licensed for use in a country, if they offer any worthwhile benefit, the vast majority of farmers quickly adopt them. This assumption is based on observation of the very rapid and near complete market penetration of Herbicide Tolerant (HT) canola in Canada (James, 2014). Some past studies modelled the likely rate of uptake of GM technologies in various countries (e.g. Dillen et al., 2009) but these estimates were based on simple assumptions of the speed and nature of GM adoption patterns of similar GM technologies in non-EU countries. As such approaches can be criticised, the simplifying assumption was made that, for each crop trait included in this evaluation, maximum penetration had been achieved. For this reason, rather than examine the potential benefits received by individual farmers of adoption of these GM technologies, it made more sense to explore the issue of the competitive advantage conferred on countries that adopt them, compared to competitors that do not. To do this, the input and output impacts of the GM traits estimated in the stakeholder consultation were applied to standard 'representative' crop cost models for a selection of EU countries (see Method section for more detail). In this exercise it was assumed that these GM technologies are taken up in the UK and the impact of this on the competitiveness of UK production, relative to a selection of northern EU countries, is assessed. The choice of the UK as the experimental platform for this competitiveness analysis is made more pertinent by the recent Brexit vote in the UK. As a consequence of this public vote, the UK will find itself outside of the EU GM licensing framework and free to follow its own GM licensing policy. Recent UK governments, guided by scientific evidence, have been notably less sceptical of GM technologies than governments in many EU countries and the European Commission and Parliament. It is, therefore, likely that the effective moratorium on GM licensing seen in the EU will not be replicated in an independent UK. It would, therefore, be instructive to explore what impact the adoption of GM technologies would have on the relative competitiveness of the UK agriculture sector.

2. Method

While there were many crop-trait combinations in the market, or under development, not all of these would be suitable for EU agronomic conditions, or offer traits that would provide benefits in the EU. A literature review was used to select appropriate candidates from within this population of options through the identification of the need for a trait to meet a particular EU agronomic challenge or, by identifying a particular crop-trait combination already discussed in the literature which might offer benefits in the EU context, for example by helping to overcome a common EU pest problem or climatic limitation (see Ricroch & Hénard-Damave, 2016; Hefferon, 2015; De Steur et al., 2015; and the GM Foods Platform (FAO, 2015)). Using these selection criteria, the EU FP7 AMIGA project team selected relevant crop-trait combinations from three official government databases of applications for release of GM material to the environment: the USDA APHIS database of field tests of GM crops (USDA, 2015); the EU GMO Register (JRC, 2015); and the Australian Applications and Authorisations for Dealings involving Intentional Release (DIR) database (OGTR, 2015). The subset of crop-trait combinations selected is presented in Appendix 1, which classifies crop-trait combinations into two broad types. First, those that have already secured USDA de-regulated status and therefore either have, or legally could be, commercialised, and second, those still undergoing trials and awaiting de-regulation.

The traits identified in Appendix 1 are expressed as broad phenotype classes. However, within these broad classes, several specific technologies might exist. For example, the phenotype class HT captures multiple technologies providing tolerance to a number of different herbicide compounds. Because of this, the counter-intuitive phenomenon is seen in Appendix 1 that field trials are still being undertaken in a phenotype class even though some representatives of that class have already achieved USDA deregulated status. Continuing the use of the HT class as an example, this occurs where developers are trying to produce HT crops tolerant either to different herbicides, or multiple herbicides as stacked traits. In the APHIS database, not only have some individual technologies been de-regulated, but they have also been commercialised, and so are currently available for uptake by farmers in some countries. To illustrate, 67% of the area of maize grown in the USA in 2013 was stacked herbicide tolerant/insect resistant (HT/IR) (Fernandez-Cornejo *et al*, 2014), while drought tolerant maize was grown on 275k ha (0.3% of the total area) in the USA in 2014 (James, 2014).

The shortlisted crop-trait combinations identified by means of this review process, had the following characteristics:

- the technology had either achieved USDA de-regulated status, or was undergoing field trials towards that objective, either in the USA, the EU or Australia;
- the technology is agronomically suitable for EU agriculture; and
- examples of this technology are either already available in the global marketplace, or stand a very good chance of being so by 2025.

The subset of 12 crop-trait combinations were further classified on the basis of whether their traits offer benefits on the input side to the farmer or grower, i.e. improved agronomic properties or, on the output side, that enhance, or modify the harvested product qualities, as shown in Appendix 1.

To carry out the Delphi study, a panel of stakeholders was recruited with expertise in GM issues from various professional sectors such as: crops research and development; arable farming; crop protection; and farm management. Invitations to participate in the study were sent to 212 individuals that had either been engaged in GM research i.e. authors of GM-related papers in peer-reviewed journals, or who were participants at recent GM-related conferences and technical meetings. These 212 individuals were drawn from a range of institutional backgrounds, with the largest group being university academics (43%), followed by commercial or government research scientists (20%) and government officials (20%). In terms of geographical location, 68% of the experts were based in Europe, 24% in North America, and 8% from other parts of the world.

An explanatory recruitment letter and a one-page questionnaire were e-mailed to the panel of experts in August 2015, and a reminder sent 30 days later, as a means to increase response rate. A total of 51 replies were received, 26 of which were sufficiently complete to be included in the final panel (an effective response rate of 12.3%). Twenty five responses were unusable, for the following reasons: 10 said they had no relevant knowledge; while 15 declined to participate for other assorted reasons. The response rate of experts working in commercial companies was much higher than for the other categories and so their weight in the final panel is greater than in the original sampling frame.

Whilst the research team would have preferred to have had a Delphi panel of more than 26, we can say, without revealing confidential details of the panel, with a degree of certainty that they were very experienced and possessed expert knowledge of the subject matter under investigation. As such they were both an appropriate and relevant panel for the study.

The second round consultation document was sent out to panel members 60 days after the first mailing. In the second round, each panel member, after being reminded of their own and the panel's average first round estimates, was invited to confirm or amend their original estimates. Of the 26 panel members, 13 replied in the second round, of whom seven made revisions to their first round estimates, while the remainder indicated that they were happy with their original estimates. For those who did not respond to the second round consultation, we could only assume that they were content to retain their original estimates. Under this assumption, the sample sizes in rounds one and two remained the same.

While more than two iterative consultation rounds are permissible in the Delphi approach, a third estimation round was not considered useful in this case because, as elaborated in the results section below (see Tables 1 and 2), the standard deviation scores associated with the group mean did not change significantly between rounds one and two, suggesting that further significant reductions in the heterogeneity of the estimates would be very unlikely. The estimates that the stakeholders were asked to make related to: (i) the impacts of the GM technologies on crop yield and production costs for input-side traits; and (ii) production costs and potential market price premia for the output-side traits. These estimates were expressed in percentage terms, referenced against those for conventional crops in 2015. Price effects can, therefore, be assumed to be expressed in constant price terms.

The analysis of the impact of these GM technologies on competitiveness was undertaken through application of revised costs i.e. estimates by the consultees of GM impacts on yield, production costs and product prices, as shown in Tables 1 and 2, to models of the cost of crop production for a number of countries using a partial budgeting approach. As data for the full costs of production were available, the impact of the uptake of GM technologies on enterprise

Net Margin was estimable. This relatively simple approach to benefits estimation, which was chosen due to constraints on data availability, was adopted in several past studies which also had the same relatively narrow focus on the estimation of producer economic benefits e.g. Flannery et al. (2004). Data for these representative cost models was derived from official sources i.e. EC directorates and national Departments and Ministries of Agriculture, as well as Government Agencies and commercial providers of benchmarking data. These data represent country-wide 'average' costs of production for non-GM crops in the case-study countries and were derived from representative survey data.

3. Results

3.1 Introduction

Summary results from the Delphi survey are presented in Table 1 (input-side traits) and Table 2 (output-side traits). These tables present the mean estimates from the whole panel of consultees for both rounds of consultation, together with a measure of the change in the variability found in these estimates from first to second round i.e. the change in standard deviation (SD) score.

When SD change scores are generally negative, this implies that the SD of the sample estimates (i.e. the extent of variation between individuals) is decreasing between rounds as the panel closes in on consensus. When the SD change estimates are also small, this suggests that there is relatively little change in the SD estimates between rounds, i.e. convergence has already largely been reached and that further iterations would only yield very small marginal reductions in variation. Statistical testing, using the Paired Comparison Students' t test at the 5% level, confirmed no significant difference ($p>0.05$) in the variability between the mean estimates of the two rounds, thus signalling no need for a further round of consultation.

Table 1. Experts' views on the likely effect of adopting various GM crops with input traits on farmers' costs and the yields obtained.

	Mean farmers' cost change (%)					Mean farmers' yield change (%)				
	1st round	SD	2nd round[2]	SD	SD change[1]	1st round	SD	2nd round[2]	SD	SD change[1]
Potato - insect resistant	-4.55	10.23	-4.47	6.49	-3.74	3.85	7.23	3.75	5.89	-1.34
Potato - pathogen tolerant	-6.38	15.58	-5.89	12.63	-2.95	9.26	8.56	9.14	7.58	-0.98
Wheat - drought tolerant	2.55	7.81	2.38	7.33	-0.48	6.85	9.40	8.00	8.32	-1.08
Soybean - herbicide tolerant	-5.75	12.85	-4.93	10.52	-2.33	4.28	6.34	4.07	5.04	-1.30
Sugarbeet - herbicide tolerant	-5.66	15.70	-4.70	13.18	-2.52	4.45	7.04	4.19	5.89	-1.15
Maize - drought tolerant	0.68	8.49	0.80	7.16	-1.33	6.08	8.32	6.73	7.15	-1.17
Maize - herbicide tolerant and insect resistant	-5.25	13.79	-4.90	12.41	-1.38	6.81	9.99	6.45	8.69	-1.30

Notes:

[1] SD change is the SD value in the second round minus the value in the first round.

[2] Differences in first and second round mean cost and yield changes were tested for statistical significance using the Students' t test at the 5% level, and no significant differences were found.

Table 2. Experts' views on the likely effect of adopting various GM crops with output traits on farmers' costs and prices for the crops received.

	Mean farmers' cost change (%)					Mean farmers' price change (%)				
	1st round	SD	2nd round[2]	SD	SD change[1]	1st round	SD	2nd round[2]	SD	SD change[1]
Wheat - with improved bread-making properties	5.29	5.42	5.47	5.22	-0.20	6.26	4.38	6.33	4.35	-0.03
Wheat - with reduced levels of protein linked to celiac disease	5.29	5.91	5.47	5.73	-0.18	9.06	7.48	9.50	7.38	-0.10
Soybean - with improved nutritional	5.13	4.99	5.26	4.81	-0.18	7.47	6.34	8.03	6.41	0.07

profile										
Oilseed rape - producing Omega 3 oils as a dietary supplement	5.39	5.83	5.23	5.67	-0.16	9.21	6.07	8.93	5.32	-0.75
Oilseed rape - with a lower lower saturated fat content	4.87	4.81	5.00	4.62	-0.19	6.63	5.25	6.68	5.18	-0.07

Notes:

[1] SD change is the SD value in the second round minus the value in the first round.

[2] Differences in first and second round mean cost and price changes were tested for statistical significance using the Students' t test at the 5% level, and no significant differences were found.

3.2 GM crops with input traits

Input-side traits offer the prospect of financial benefits to farmers from reduced input costs, especially crop protection costs (such as less expenditure on herbicides and pesticides), and increased revenue through improved (or protected) yields. Table 1 shows that the panel anticipated cost savings from five out of seven input-side traits, but increases in production costs in the remainder. Costs savings ranged from 4.47% to 5.89%, a relatively narrow range, with these being somewhat larger in magnitude than the range of expected cost increases i.e. 0.80% to 2.38%.

The crop-trait combinations offering the largest savings in input costs are pathogen tolerant (PT) potato (5.89%) and HT soybean (4.93%). At the other end of the spectrum, the panel thought that drought tolerant wheat would raise farmers' costs by 2.38% due to the fact that there would be no crop protection cost savings to compensate for higher seed costs. The notion of increased production costs for drought tolerance makes perfect sense because, with the possible exception of reducing the need for irrigation, these traits do not replace any inputs, such as sprays, but they may incur higher seed costs. However, these traits may still prove financially advantageous if their yield protection benefits, in years of drought, offset the higher seed costs when averaged over the longer term.

The highest and lowest anticipated yield improvements (Table 1) are both recorded for potatoes, with IR potato estimated to lift yield by 3.75%, and PT potato by 9.14%. This suggests a panel consensus that current yield losses from insect pests, e.g. Colorado and Flea Beetles, are considerably lower than yield losses from diseases, such as Brown Rot and Late Blight. It is informative to note that most of the recent GM potato trials globally have been for late blight resistance. Drought tolerance is estimated to offer greater potential yield benefits than the average, at 8% for wheat and 6.73% for maize. These estimates are high considering that they represent yield protection averaged over a number of years. This strongly suggests the stakeholder view that yield losses in drought years might be catastrophic. Herbicide resistance traits are estimated to offer slightly below average yield improvements for both sugar beet (4.19%) and soya bean (4.07%).

3.3 GM crops with output traits

The panel anticipated that all of the crops with output-side traits would incur increased production costs compared to the conventional equivalent (see Table 2). These cost increases would be due, almost in their entirety, to higher seed costs, as biotech companies attempt to recoup their investment in product development. The stakeholder panel provided a pretty narrow range of production cost increases across crop-trait combinations, with a range of just 0.47%. Interestingly, the crop expected to incur the largest increases in production (seed) costs, is wheat, i.e. 5.47% for both output traits. Here, stakeholders may be factoring in the fact that wheat is a relatively high value crop (per hectare), and so can better support higher seed prices than some other crops. At the other end of the scale, the output trait with the smallest increase in production costs was OSR with lower saturated fat content (5.0%).

All of the nutritional profile changes identified for GM crops were viewed as being desirable to consumers and, so, all were expected to offer a price premium to the farmer. However, they all represent niche markets so only a fairly small sub-set of farms would be able to grow them. The highest price premium was anticipated for wheat with reduced levels of protein linked to celiac disease (9.5%), although this would only be a niche market product. Oilseed rape producing Omega 3 oils as a dietary supplement was also expected to offer a substantial premium (8.93%). The crop with the lowest estimated premium, by comparison, was wheat with improved bread making properties (6.33%). This slightly lower premium, in comparison, may be due to the fact that the gains to bread and biscuit makers from the new properties would be only marginal, as this trait would not allow for any new differentiation in the market and so a higher retail price would not be obtainable. However, the panel did not give any 'hard' evidence in this respect.

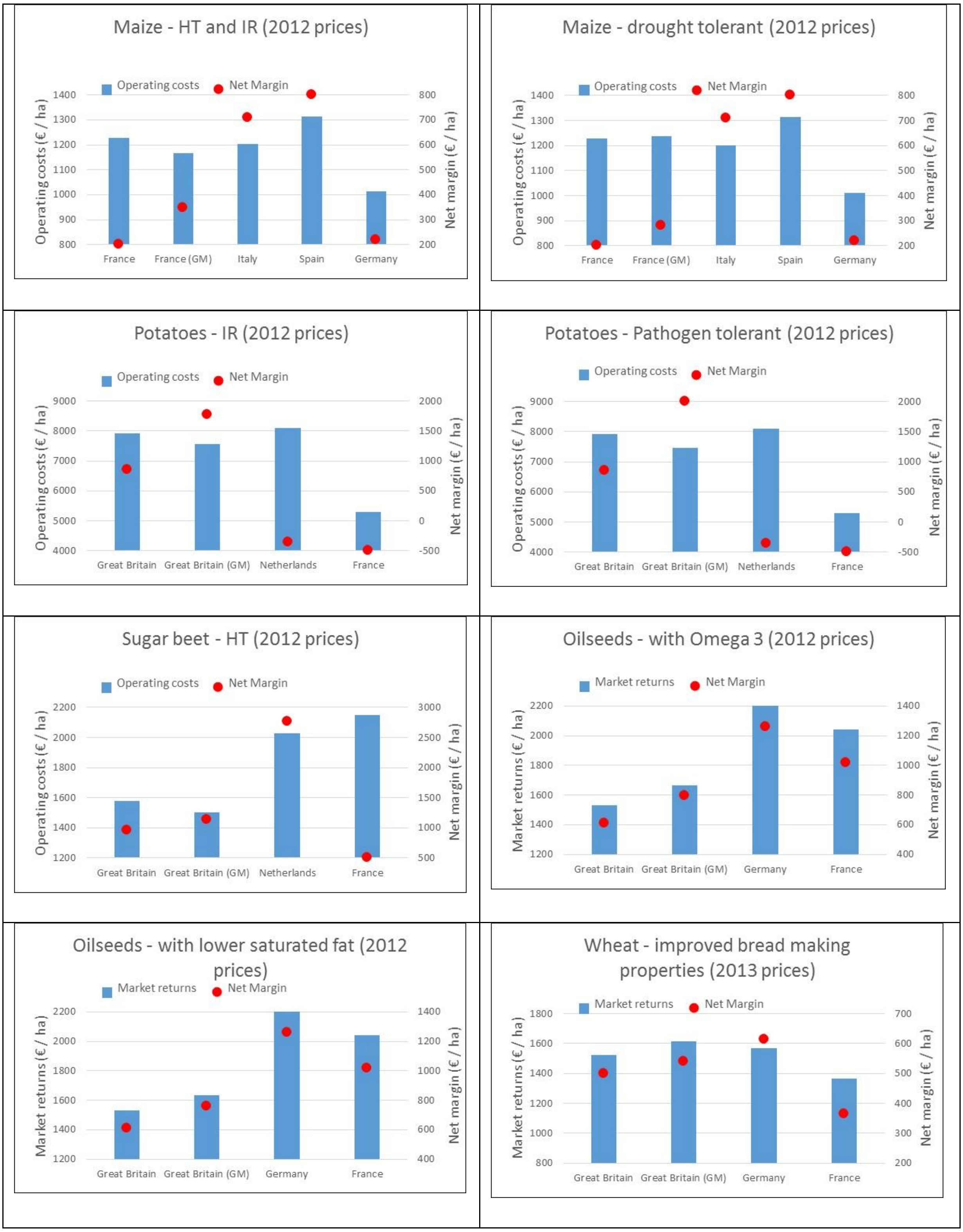
3.4 Impact of the 'new' crops on competitiveness

The significance of these GM technologies i.e. their impact on competitiveness, was explored by comparing GB enterprise production costs and market returns (i.e. sales value without subsidy), both with and without GM, to equivalent non-GM production in selected EU countries. Figure 1 shows the impact of GM adoption on competitiveness, as expressed by market returns and net margin for output-side traits, and operating costs and net margin for input-side traits. The adopter country (i.e. where GM technologies have been applied) is GB agriculture for six out of eight crop-trait combinations, but France had to be used in the two grain maize cases, as grain maize production does not occur in GB.

Figure 1 suggests that, assuming widespread adoption, the selected GM traits could improve the competitive position of GB agriculture compared to non-adopting EU counterparts. The way in which this improvement in competitiveness is achieved varies according to trait. For input-side traits, competitiveness is improved by reducing production costs. For example, in the case of potatoes, current GB production costs are roughly equivalent to those in the Netherlands. However, the adoption of GM pest control technologies for this crop i.e. HT and pathogen tolerance (PT) would reduce average GB production costs by 4.5% and 5.9% respectively (see Table 1) to a level significantly below that in the Netherlands. If these cost savings could be passed on to consumers in the form of lower prices, GB potatoes could, perhaps, compete for market share in the Netherlands, despite the additional transport costs.

In the case of output traits, the panel thought that costs of production are, more often than not, expected to increase, as in the case of OSR with enhanced Omega 3 content, where production costs were projected to rise by 5.2% (see Table 2). Whilst this would lead to higher consumer prices if consumers placed a higher value on this 'enhanced' product, they would be willing to pay these higher prices. If the monetised value that consumers placed on the enhanced product was greater than the production cost increases, then a producer (price) surplus would be available, as indeed is projected in this case, with an expected rise in producer price of 8.9% (see Table 2). Competitive advantage would also be improved through gaining access to a niche market that non-adopters could not exploit.

Figure 1. Impact of the uptake of selected GM technologies on the competitiveness of crop production in Great Britain and various EU countries.



Sources: EC (2016b); AHDB (2015); Defra (2013); Rezbova et al. (2013); USDA (2012); AgriBenchmark (2016); and EC (2012).

Note: Wheat and grain maize enterprise data are based on FADN whole-farm data for farms specialising in those crops.
Note: Potato prices are based on a 3-year average centred on 2012 to smooth out extreme annual variation.
Note: Data originally denominated in £ Sterling have been converted to Euros, assuming an exchange rate of £1=€1.2.
Note: NL sugar beet production costs (2012) are assumed to be the same as in DE.
Note: The average EU rapeseed price (2012) has been used for DE and FR.

Competitiveness is also indirectly improved, for all traits considered here, through increased profit (i.e. Net Margin). More profit means more capital is available for investment in: technological innovation through new machinery purchases; land purchases to spread fixed costs; or through enhanced training and advisory services. These investments drive increases in technical and managerial efficiency, thereby securing further improvements in competitiveness. Improvement in competitiveness of this kind is best exemplified by wheat with improved bread-making properties (see Figure 1). GB adoption of this GM technology would increase wheat production costs by 5.5% i.e. rising above average costs in Germany, but would elevate profits by 8.1% through an increased price premium (of 6.3%), thereby enhancing the prospect of additional future UK investments leading to improvements in efficiency.

3.5 Identification of other crop-trait GM combinations that might become available

The selection of crop-trait combinations used in the study reported here was made on the basis that the technologies were either already in the market, or well along the development pipeline and would also offer potentially significant benefits to EU farmers or consumers. These particular crop-trait combinations were chosen because they captured the most important trait types, across a range of major crops. To guard against the possibility that important crop-trait combinations had been omitted from the Delphi consultation, panel members were asked to suggest any such alternatives that also met the selection criteria. Only a small number of GM crop-trait combinations were suggested by the panel, these being dominated by output-side traits i.e. various types of biofortification. Most of these output-side traits would supply niche markets, which are by nature, small. Therefore, there would only be very limited opportunities to tap into these markets to secure a price premia. Such traits, therefore, offer only modest benefits for the broader farming sector and wider society. In light of this it is, perhaps, not damaging to the analysis presented here that some GM traits of this type have been omitted. Of course, some output-side traits, for example vitamin fortification, might not be confined to niche markets but could, in theory, displace all conventional production. However, while the potential market for such traits is, in theory, very large, the scale of the benefits to both farmers and wider society within the EU are likely to be small. There are two reasons for this. First, when a GM crop displaces its conventional equivalent, even if some additional societal benefit is being supplied, market prices tend to drop to the same floor as in the former conventional market. Second, in any developed country where diets are already nutritious and where many fortified processed products already exist, the price premium for a biofortified commodity would be small, reflecting the small marginal societal gain.

A minority of the panel of stakeholders, when asked to identify prospective GM technologies that were not included by our review, pointed away from traditional GM technologies instead to the products of new plant breeding techniques (NPBTs), such as CRISPR, which do not use transgenesis. Although relatively new, techniques such as CRISPR are already being hailed (for example, see Belhaj *et al*, 2013; and Ledford, 2015) as the future industry standard tool for biotechnology, thereby likely to supplant GM in plant breeding. While the status of these NPBTs are currently still being debated by advisory bodies and regulatory authorities in the EU (Tagliabue, 2016), the hope is that because they produce plant gene modifications that are indistinguishable from both conventional breeding and chemical and physical mutagenesis, they will be excluded from the scope of GM legislation such as Directive 2001/18/EU on Deliberate Release of Genetically Modified Organisms. This would make releases of such crops to the EU market much more routine.

4. Discussion and conclusions

Our choice of a stakeholder consultation approach for generating estimates of likely yield, cost and revenue changes resulting from future EU (or UK) adoption of GM crops allowed a nuanced transfer of data from non-EU settings into the EU context where crop-trait combinations have already been developed and has also allowed for the generation of 'novel' data where crop-trait combinations are still in development. The extent of the challenge facing the consultees in transferring data from non-EU settings depended on several factors, including perceptions of whether there are likely to be differences in seed costs, or agronomic differences between the EU and non-EU settings that had to be accounted for, plus differences in disease pressure and pest management practice.

Another important consideration that consultees had to account for was the likely costs associated with required co-existence measures in adopter countries, as these could impact considerably on production costs. The specific measures that might be put in place in the adopter countries for individual crops could not, perhaps, be easily anticipated, so it is not exactly clear how consultees handled this issue. However, it is likely that reference would have been made to the impact of co-existence measures on production costs in countries that had already adopted similar GM technologies. It is also worth pointing out that the existence of co-existence measures in these non-EU countries has not acted either as a barrier to rapid uptake, nor significantly eroded the financial benefits that the technology confers (see, for example, Furtan et al, 2007), including the case of GM maize in Spain and Portugal.

The cross-country analysis reported here provides a useful indicator of the impacts that GM crop adoption would have on national competitiveness. However, it should be recognised that this analysis presents a somewhat simplified picture of possible future adoption decisions. First, the analysis assumes near complete uptake of these GM technologies in the adopter country. While this must be a reasonable assumption for some of these GM technologies based on historic observation, for example PT potatoes would likely be widely adopted as all growers could benefit. However, this might not be the reality for some crop-trait combinations, for example where the GM technology targets a particular pest problem that is not present in all regions within a country. A historical example of this would be the adoption of IR maize in Portugal, where uptake has been confined to regions where European/Mediterranean Corn Borer presents a significant commercial risk (Jones et al, 2017). For crops with limited potential for market penetration, for example DT maize, the results of the competitiveness analysis should not be interpreted as indicating the impacts for the competitiveness of the countries as a whole.

Second, the data used in the representative cost models are reflective of the central tendency in each case-study country. In reality, a wide distribution of production costs exists in each country, due to diversity in farmers' management ability, agronomic factors and geographic location. This means that changes to the competitive advantage resulting from GM adoption would not be uniformly experienced amongst producers in any country.

Third, the consultees' estimates of GM impacts in costs and yields are themselves also measures of central tendency, obscuring a likely broad range of impacts experienced by individuals, where some, due to their particular circumstances, may not receive significant benefits from the technology. Finally, the possibility must be considered that the consultees, in considering the impacts of the GM technologies on production costs, did not properly factor in possible increases in costs associated with some potential negative externalities of adoption of GM technologies, such as increase in pest resistance through the use of HT or IR events (Green & Owen, 2011; Brookes, 2014). In such circumstances, additional management actions are required to control the problem, perhaps involving applications of alternative pesticides requiring more sprayer passes, or other approaches to pest control, such as changed rotations, or use of deep mechanical tillage.

Whilst resistance problems can be controlled by careful use of conventional management techniques, the need to undertake them can remove some, or all, of the cost saving benefits from the use of the technology (Green & Owen, 2011). Numerous other studies have claimed a range of environmental and social dis-benefits arising from the widespread adoption of GM technologies, such as gene-flow to non-GM crops (Mallory-Smith & Zapiola, 2008) and wild relatives (Warwick, et al., 2008; Reichman, et al., 2006), damage to wildlife (Garcia & Altieri, 2005) and even economic risks to non-GM producers through adventitious contamination (Blakeney, 2016). There is insufficient space to critique these studies and claims here, although it is worth noting that several authors have cogently argued that the environmental and socio-economic benefits of GM crops far outweigh any negative externalities (Brookes & Barfoot, 2016). Whilst this lack of detailed critique may seem unsatisfying to some, it should be pointed out that for the analysis here there is the requirement to do so, as the focus of the study reported here is on the impacts of adoption of

GM technologies in the EU on potential producer surplus, rather than consumer, or wider societal surplus.

The historic policy environment in the EU has resulted in an effective moratorium on GM releases to the environment. With most consumers, campaigning groups and politicians across the EU remaining largely hostile to the production of GM crops and the consumption of their products, it is understandable that many of the stakeholders consulted were of the view that the current informal moratorium on GM authorisations would remain in place for the foreseeable future. While the GM policy environment has changed in the last few years, there is still great uncertainty over whether this will make GM authorisations more likely, as many states are likely to execute the opt-outs permissible under the new legislation. For example, it is already known that 19 Member States had applied for the opt-out prior to the 3 October 2015 deadline for applications to the Commission, including: Germany, France, Italy, Austria, Greece, Hungary, Latvia, Lithuania and Poland (New Scientist, 2015). Additionally, even if authorisations begin to flow, it is not known whether GM crops would actually be accepted into these national markets by retailers and consumers.

The uncertainty revealed here by our consultation over the future market and policy environment will, of course, do little to change the attitudes of biotech companies towards investment in biotechnologies targeted at EU agronomic conditions or, indeed, those seeking authorisations for GM crops to be grown in the EU. If this generally pessimistic stakeholder outlook is a harbinger of restrictive future EU policies, and is a disincentive to biotech companies to invest in GM crops targeted at EU agriculture, then the benefits associated with GM crops identified here must be viewed, in essence, as benefits that will be foregone by the great majority of EU farmers.

In terms of the scale of these benefits foregone, the study reported here has shown that the competitiveness of the agricultural sector in EU Member States could very well be improved by adoption of GM crops. However, these improvements, when averaged over all farmers in a country, would still be relatively small-scale, to the extent that existing large-scale natural advantage, resulting from relatively durable macro-economic or environmental conditions, is very unlikely to be overturned. For example, the adoption of HT/IR grain maize in France would, in terms of country-wide averages, overturn the current small competitive advantage that Italy holds, but would do little to eliminate the much more significant competitive advantage (resulting from lower costs of production) held by Germany. Adoption of GM crops would, therefore, not be a game changer for countries with high production costs, although they would, based on the evidence generated in the study reported here, make a positive contribution with respect to competitiveness in any country that adopts them.

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Appendix 1. The various GM crops, and their traits, shortlisted for the Delphi survey.

Crop	Phenotype class	Year of first field test notification (APHIS)	IP owners (trials in last 5 years)	No. of trials in last 5 years	USDA unregulated status granted (and IP owners)?	Sources used to identify suitability for EU agriculture
Maize	Drought tolerance	Unknown	Pioneer Hi-Bred International Inc; Monsanto.	>15	Yes Pioneer Hi-Bred International Inc.; Monsanto; BASF; Syngenta.	Ferrero *et al* (2014) Tolk *et al* (2016)
Maize	HT-IR stacked	1992 Pioneer Hi-Bred International Inc	Monsanto & Monsanto Europe, S.A.; Syngenta Crop Protection LLC; Pioneer H-Bred International Inc; Dow AgroSciences LLC; Genective SA; Bayer CropScience; Genective SA; Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA).	>15	Yes Monsanto; Pioneer Hi-Bred International Inc.; Syngenta; Aventis; Novartis Seeds.	Baktavachalam *et al* (2015) Ruffo *et al* (2015)
Potato	IR	1990 Monsanto	Michigan State University.	>15	Yes Monsanto; Frito Lay; USDA; Calgene.	Haeseart *et al* (2015) Jo *et al* (2014)

Crop	Phenotype class	Year of first field test notification (APHIS)	IP owners (trials in last 5 years)	No. of trials in last 5 years	USDA unregulated status granted (and IP owners)?	Sources used to identify suitability for EU agriculture
Potato	Fungal resistance (FR)	1990 Washington State University	J.R. Simplot Company; Michigan State University; Betaseed inc.; John Innes Centre, UK; Swedish University of Agricultural Sciences SLU; Wageningen University; Teagasc; BASF Plant Science GmbH; Queensland University of Technology.	>15	Yes USDA; Monsanto; Washington State; Frito Lay.	Haeseart *et al* (2015) Jo *et al* (2014)
Sugar beet	HT	2004 Syngenta	Betaseed inc; Ses Vanderhave NV; Syngenta Crop Protection AG; Plant Production Research Center Piestany, Bratislavska cesta; KWS SAAT AG; SESVANDERHAVE N.V.; Monsanto Europe SA.	5-10	Yes American Crystal Sugar Company; Syngenta; Betaseed; Ses Vanderhave NV.	Dillen *et al* (2013)

Crop	Phenotype class	Year of first field test notification (APHIS)	IP owners (trials in last 5 years)	No. of trials in last 5 years	USDA unregulated status granted (and IP owners)?	Sources used to identify suitability for EU agriculture
Soyabean	HT	1989 Monsanto	Pioneer H-Bred International Inc; M.S. Technologies LLC; Monsanto; Bayer CropScience; University of Georgia; USDA; Iowa State University; University of South Carolina Aiken; BASF Plant Sciences LLC; DAS LLC; Syngenta; Montana State University; OSU-OARDC.	>15	Yes University of Georgia; Upjohn; Northrup King; Pioneer Hi-Bred International Inc; M.S.Technology LLC; Monsanto.	Brookes (2003)
Soya bean	PQ (improved nutritional profile)	1993 Du Pont	Pioneer H-Bred International Inc.; University of Kentucky; USDA; University of Minnesota; Monsanto; University of Missouri; University of Nebraska/Lincoln; University of Kentucky; Montana State University.	>15	Yes Du Pont; Monsanto; Pioneer H-Bred International Inc.	Sowa *et al* (2014)

Crop	Phenotype class	Year of first field test notification (APHIS)	IP owners (trials in last 5 years)	No. of trials in last 5 years	USDA unregulated status granted (and IP owners)?	Sources used to identify suitability for EU agriculture
OSR /canola	PQ (Lower saturated fat content)	1991 Calgene	None	None	Yes Calgene; Cargyll; InterMountain Canola; Du Pont.	Batista *et al* (2011)
Wheat	Heat/drought tolerance	1998 (Montana State University)	Syntech Research; Arcadia Biosciences; University of Nebraska; Southern Illinois University; Monsanto; Biogemma USA.	>15	No	Farooq *et al* (2014) Aschonitis *et al* (2013) Yadav *et al* (2015)
OSR /canola	PQ (higher Omega 3 oils)	2014 Nuseed Americas	Nuseed Americas.	1-4	No	Batista *et al* (2011)
Wheat	PQ (Biologically safe, e.g. for coeliacs)	2011 Washington State University	Washington State University.	1-4	No	Gil-Humanes et al (2010)
Wheat	PQ (improved bread-making quality)	2003 Montana State University	USDA; Murdoch University, Australia.	5-10	No	Graybosch *et al* (2013)