Insights into global food system risks and opportunities and their implications for the FSA

Final report

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Acronyms

CRISPR	clustered regularly interspaced short palindromic repeats
Defra	Department for Environment, Food and Rural Affairs
DNA	deoxyribonucleic acid
DLT	distributed ledger technology
FSA	Food Standards Agency
MRLs	maximum residue levels
PESTLE	political and regulatory [P], economic [E], social and cultural [S], technological and scientific [T], legal [L], and environmental [E]
STREAM	systematic technology reconnaissance, evaluation and adoption methodology

Acknowledgements

1. Introduction

The UK Food Standards Agency (FSA) needs a long-term perspective on the global food system in order to anticipate and respond to issues that may affect the activities within its remit. To this end, the FSA and its Science Council commissioned RAND Europe to identify and assess global food system risks and opportunities and to draw out key issues and their implications for UK food safety and authenticity[1] to 2030.

Achieving a long-term perspective requires a foresight approach that is framed, from the outset, in terms of the wider global food system context and in terms of the specific responsibilities, needs and objectives of the FSA with respect to food safety and authenticity (UK Government 1999). For this study, we used a prioritisation foresight approach developed at RAND and previously employed in both a UK and a US policy context. The exercise undertaken for this study is intended to establish a baseline for the FSA's foresight work. It was designed to operate as a test of an approach that the FSA could implement to enable ongoing capabilities in this area. Four main objectives guided the research:

- **Objective 1 – Framing:** Develop an informed and integrated view of the global food system.
- **Objective 2 – Scanning:** Identify specific novel and emergent food system themes and their associated trends, pressures and drivers.
- **Objective 3 – Prioritisation:** Establish particular themes of relevance to the FSA to 2030.
- **Objective 4 – Translation:** Assess potential approaches the FSA could take to implement ongoing foresight capability.

These objectives guided the development of the methodology, described in Chapter 1. Chapter 3 provides the study results, and Chapter 4 reflects on future actions for the FSA, particularly regarding further foresight activities.

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[1] Food authenticity refers to food that matches its description. The description of food refers to the information given about its name, ingredients, origin and processing (FSA 2018c).

2. Approach and methodology

Foresight, or 'futures', analysis aims to identify long-term issues and challenges and explore their implications. The use of these approaches emerged from the significant increase in research funding to support technology development for military purposes during WWII and throughout the Cold War to more systematically assess how these technologies might evolve and to consider how they might be used. Several methodologies designed for these purposes were first developed at RAND in the 1950s and later applied to fields outside the military domain.

For this study, we applied the principles of a foresight methodology developed at RAND in 2013 – the systematic technology reconnaissance, evaluation and adoption methodology, also known by the acronym STREAM (Popper et al. 2013). STREAM has been applied in studies in UK defence and security, UK and US transportation, and US law enforcement. The method as typically used focuses specifically on technology assessment, but in this study, the issues considered are not only scientific and technological, but also socioeconomic. The study therefore built on tried-and-tested methodologies, developed and used extensively at RAND, that were made bespoke to meet the FSA's specific needs.

2.1. Phase I – Frame

The first phase of the project involved establishing a framework to assess food system themes and issues. The study team conducted an initial scan of the academic and 'grey' literature and selected eight reports[2] published in the past five years on the current and future UK food system and focused on issues identified by two or more of the reports as being particularly relevant for the current and future UK food system. The study team then undertook a wider search for news articles and other reports from the past five years that mention these issues and their impacts, which led to an examination of more than 90 sources. The combined searches resulted in a total of 25 issues identified by one or more of the sources as having particular significance for and impacts on the current and future UK food system. Based on these issues, the study team considered PESTLE factors (referring to political and regulatory (P), economic (E), social and cultural (S), technological and scientific (T), legal (L), and environmental (E)) to identify four general areas of importance: namely, consumer, technology, industry and environment. The team also identified macro- and micro-level themes. It then examined the interactions of these themes with these areas.

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[2] Colwill et al. 2016; Defra 2010, 2016; Fabian Society 2015; Food Foundation 2016; IFST 2017; Fitzpatrick & Young 2017; TNS BRMB & FSA 2016.

The PESTLE analysis provided the basis for a global food systems map (Figure 1, Section 3.1), which was designed to provide a graphical representation of these themes and areas to act as a reference point for analysing the global food system. It was updated throughout the study based on advice and inputs from the FSA Science Council, expert interviews and participants in an expert workshop.

Logic models are intended to make their users think systematically about the different elements of a programme, the assumptions underlying the programme and other external factors potentially affecting the achievement of the ultimate outcomes (Guthrie et al. 2013). We developed a logic model (Figure 2, Section 3.1) which presents our understanding of the FSA's policy activities, objectives and operations. It was developed through desk research of relevant sources from the FSA, including strategic plans, policy documentation (e.g. *Regulating our Future* report (FSA 2017b)), annual reports and communications from board meetings.

Phase I concluded with establishing assessment criteria and search terms (Appendix 6.1) to inform a horizon scanning literature review to be undertaken in Phase II. The criteria and search terms build on the global food systems map and logic model, a further review of documentation from the FSA, other relevant government bodies, news agencies, and food and farming associations, as well as academic articles. The search terms were not designed or intended to be used for a systematic review approach, which would be beyond the scope of and resources available for this study. Our approach, which has been used by RAND Europe for foresight and horizon scanning for UK government departments, relied on rapidly identifying signals that could be of relevance, and then applying further research to assess the authority of the source.

2.2. Phase II – Identify and characterise

Horizon scanning is a formal process of gathering information to support decision making (Popper et al. 2013). We used the search terms identified in Phase I as the basis for a semi-structured search of science news aggregator websites, academic publications, market research organisations, and food technology websites. Each identified item was entered into a database, where it was assigned keywords and scored according to evidence authority, novelty, probability of realisation and relevance to the FSA. The robustness of the scanning procedure was assessed through re-scoring of a subset of items by the three researchers involved in the process.

Next we used two approaches to group information, focusing on a set of themes that the study team identified as important for the FSA based on the logic model. First, we identified the most frequently assigned keywords and grouped these to form cohesive themes. Second, we selected a set of potential weak signals – themes that were not frequently cited in the literature but that the team considered to be important future considerations based on our knowledge and understanding of the theme and its relevance to the FSA. During this stage, the global food systems map evolved to include themes that were not present in the initial version and to take into account newly identified relationships between themes.

Informed by the scanning and categorisation tasks, we selected eight themes for further investigation by considering the most frequently assigned keywords and forming cohesive themes from related items and, also, by considering potential weak signals – early signs of change that may have major impact in the future – that either scored highly or were identified by the scanning team. The output was a set of

'thematic briefs' (Section 0) on topics that fulfil the assessment criteria defined in Phase I and that informed interviews with practitioners, experts and researchers in Phase III.

2.3. Phase III – Compare and decide

The third phase of the study involved a prioritisation process to identify the overarching themes and subthemes of most relevance to the FSA and explore the connections and interrelationships between them. Fifteen interviews were conducted with specialists in one or more fields reflected in the themes, and these interviews were used to identify priority themes, relationships and additional 'weak signals'. This information was used to create a map of systemic interdependencies (Figure 3, Section 3.3), illustrating how different elements of the global food system influence each other and which areas have a particularly strong effect on the system. We then developed a framework (Figure 4, Section 3.4) for mapping the pathway from the challenges currently facing the global food system towards the goals of maintaining a UK food system that is safe and authentic, within a constantly changing global food ecosystem. The global food system map, the map of systemic interdependencies, and the framework, along with the eight thematic briefs, guided discussion in an expert workshop led by the FSA with the support of the study team. Workshop participants were invited to suggest modifications to the maps as well as contemplate pathways that chart a course from the challenges facing us today to reach an 'idealised' food system. As a result, the workshop helped refine the findings, identify gaps and significant 'unknowns', and reflect on the subsequent steps a regulator might wish to consider, including ongoing foresight activities. Following the workshop, RAND Europe conducted an evaluation of the exercise and its ability to serve as a baseline for the FSA's potential future foresight and horizon scanning work compared with other approaches. Appendix 6.2 lists the experts who participated in the interviews and those who attended the workshop.
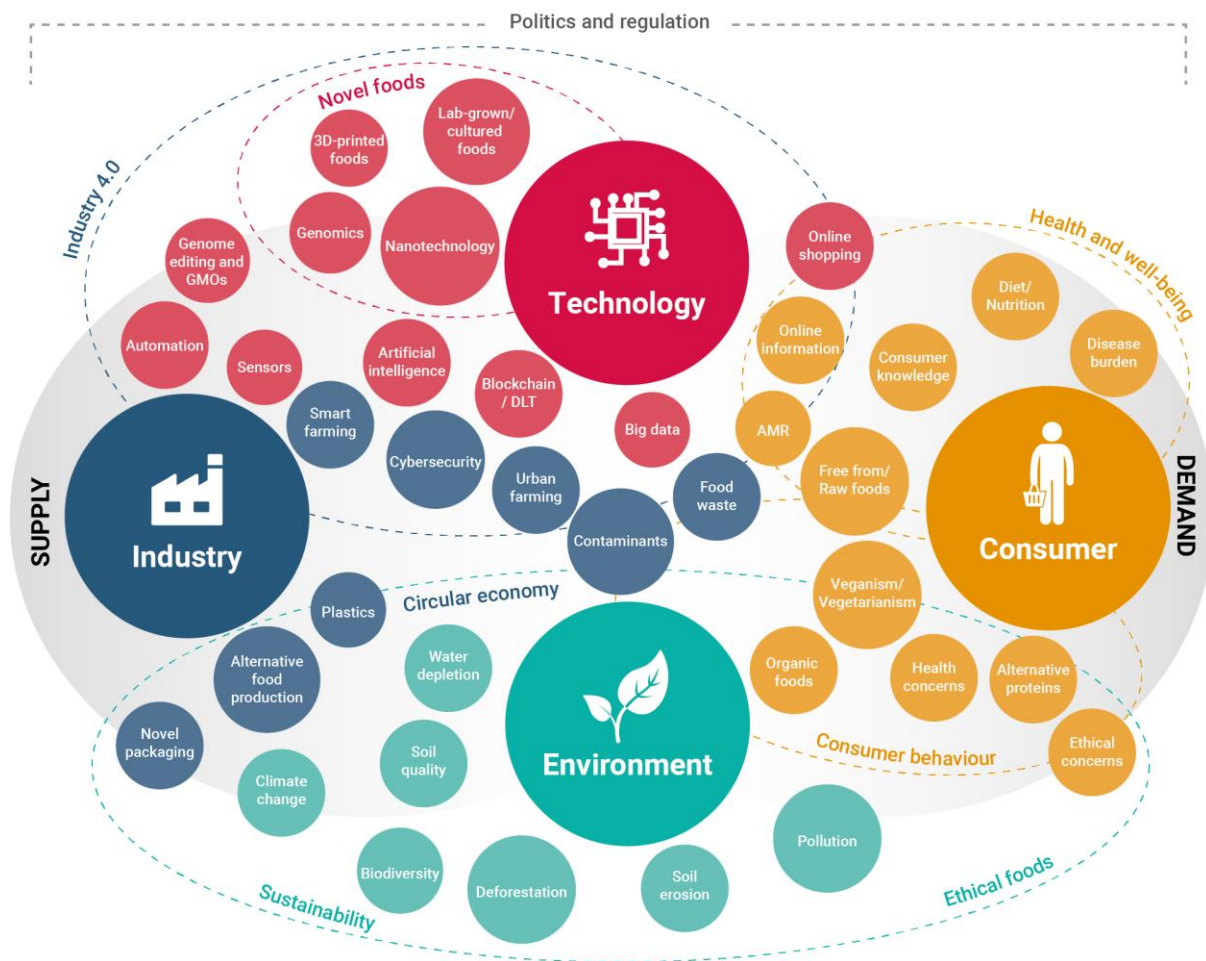
3. Results

The study resulted in a global food systems map, a logic model for the FSA, a set of thematic briefs, a map of systemic interdependencies, and a framework illustrating the pathway from challenges to goals to support an 'idealised' food system that remains safe and authentic. None were fixed or final when first developed; instead, they were intended to evolve further in later phases of the study based on the evidence emerging at each stage of the research. Together, they offer a baseline for future foresight activities undertaken by the FSA.

3.1. Mapping the global food system and identifying FSA priorities

Figure 1 provides a graphical representation and a reference point for analysis using a 'systems' approach, that is, to see the global food system as a complex policy space. Indeed, it can be considered a complex adaptive system (Nesheim et al. 2015) with many interconnected and interdependent features (Ingram 2011). The map identifies four general areas – consumer, technology, industry, environment – and also shows macro- and micro-themes that could have a positive or negative impact on the global food system. These themes constitute either a risk, an opportunity, or both to the UK food system.

In the foresight exercise for this study, considering the food system as a complex adaptive system implies that interconnections and feedback between the food system and other related systems, such as health, agriculture, climate and energy, should be considered and, equally, that the food system cannot be assessed in isolation (Nesheim et al. 2015). New technologies and changing behaviours, as well as disruptions or failures in any of these systems, can have consequences on the others; for example, the continued development of sensors could help improve decontamination efforts and lower pollution levels in food processing plants.

Figure 1: Map of global food systems

Source: RAND Europe analysis

The FSA logic model (Figure 2) links its mission with its policy activities and identifies the inputs and processes that are needed now in order to obtain desired outputs and outcomes, or results, in the future. The logic model provides a way of articulating a pathway by which the FSA achieves its aims, and identifies outcomes that can be causally linked back to concrete inputs. The logic model was developed to ensure FSA priorities were woven into the study design from the outset and was a reference point for the analysis throughout.

Figure 2: FSA logic model

Influencing factors

Increased pressures on food supply

Food trade and sustainable development

Innovation in food technologies

Political events

Inputs

FSA strategy, policy, and legislation

Collaborations and strategic partnerships

Governance: FSA Board and Executive

Advice: Scientific Advisory Committees/Council

Systems for surveillance, monitoring, intelligence

Resources (e.g. funding, expertise, equipment)

Activities

Develop, enforce, review safety and authenticity regulation at every stage of the food chain

Engage in surveillance, monitoring and analysis

Gather and use scientific evidence

Develop cost-effective ways to support businesses to be more transparent

Disseminate information to consumers on food safety, authenticity and nutrition

Develop and deliver evidence-based programmes and strategic plans

Advocate for adoption of current and future innovations

Outputs

Legislation and guidance on food safety and authenticity in place throughout UK food chain

Documents on food safety and authenticity available to the public

Intelligence on food safety and authenticity available to local government and law enforcement partners

Outcomes/impacts

Food is safe

Food is what it says it is

Consumers have access to an affordable and healthy diet, and can make informed choices about what to eat

Consumer organisations

Industry representatives

Local authorities

NGOs

Academic and scientific community

Cross-government teams

Stakeholders

Source: RAND Europe analysis

3.2. Thematic briefs of key issues affecting future food systems

Informed by the scanning and categorisation tasks described in section 3.1, the study team identified eight themes for further investigation that are of most relevance to the FSA:

- Alternative food production methods and technologies (3.2.1);
- Alternative proteins (3.2.2);
- Consumers (3.2.3);
- Contaminants (3.2.4);
- Synthetic biology (3.2.5);
- Genomics (3.2.6);
- Packaging and food waste (3.2.7); and
- Sensing and data-driven decision making (3.2.8).

Our aim was to contextualise findings on issues identified within the themes and to link back to the FSA priorities identified in the logic model (Figure 2). The in-depth investigations served a dual purpose: initially, informing a series of interviews with practitioners, experts and researchers and, subsequently, providing concise summaries of eight aspects of food systems that are likely to impact the UK in the mid- to long term (four to ten-plus years).

Each thematic brief follows the same structure, providing an introduction, an exploration of the key issues within the theme, and a discussion of the relevance to UK food systems. The level of relevance was determined by the project team according to the logic model presented in Section 3.1. The issues and examples identified in the eight thematic briefs were identified through a horizon scanning exercise. The issues were selected through a prioritisation exercise, and examples were chosen from the literature explored during the horizon scan to illustrate each issue. The issues presented below thus do not represent an exhaustive list of key issues.

3.2.1. Alternative food production methods and technologies

Alternative food production encompasses methods that do not follow conventional food supply chains. These methods can involve different inputs, processes, environments and outputs to land-based, intensive agriculture. Drivers for alternative food production include growing recognition of climate change as a global challenge, consumer demand for sustainably and locally produced food and exhaustion of natural resources (Gracia & de-Magistris 2016; Henchion et al. 2017).

Key issue: changing approaches
Changing methods of food production can affect all subsequent steps of the food chain. Food may be exposed to different chemicals and contaminants, spoil at different rates or have different nutritional profiles. There are a range of drivers for changing production methods. The emergence of new technology can enable new approaches, and economic pressures may force producers to employ new methods. Additionally, consumers increasingly demand knowledge about food production methods and may drive development of certain methods through their purchasing power (Hancock 2017).

- **Aquaculture**, that is, the farming of aquatic organisms, is one of the fastest growing food production systems; it is on course to exceed the fish capture sector as soon as 2019 (FAO 2017; Terazono 2017). Research demonstrates that the world's oceans are capable of accommodating further large-scale aquaculture development, which could greatly enhance food security (Wang 2017; World Bank Group 2016). Global fish production significantly contributes to fish meal and oil production, and thus indirectly contributes to human food production (Jennings et al. 2016). However, intensive aquaculture has associated risks, including nutrient pollution, increased pressure on wild fish stocks for feed, and the emergence of new and highly virulent pathogen strains (Jones & Downing 2009; Sundberg et al. 2016). In addition, there are risks to social and economic sustainability that result from low financial viability of production systems and their low resilience to shocks (Jennings et al. 2016).

- **The organic food and drink sector** has grown for six consecutive years in the UK. In 2017, it rose by 6 per cent, to reach £2.2bn out of the approximately £113bn agri-food market (Defra 2017; Soil Association 2018). Demand for organic produce is linked to growing demand on the part of consumers for products they perceive as healthy, tasty and sustainable (IPSOS Knowledge Centre 2018; Olson 2017). Consumers assign different priority to each of these factors (Magnusson et al. 2003; Shafie & Rennie 2012). However, consumer demand is limited by unequal access to the organic food market for UK consumers, as some consumers assume that they cannot afford organic food because of the premium price (Shafie & Rennie 2012). There is also ongoing debate in the food nutrition literature regarding the health benefits of organic food (Baranski et al. 2017; Dangour et al. 2009).

Key issue: new technologies

Emerging technologies can support conventional or alternative production methods, helping to safeguard the food supply, reduce production costs and decrease potentially damaging environmental effects.

- **Ultraviolet (UV) treatment of crops** appears to be gaining commercial ground. New Zealand firm BioLumic recently raised $5m for its UV crop yield enhancement system, which is being implemented in many countries for commercial use, with yield gains of up to 22 per cent (Wang 2018). UV treatment can also be used to increase the shelf life and nutritional profile of fruits and vegetables through activation of defence responses and inhibition of microbial growth (Erkan et al. 2008).

Relevance to UK food systems

Aquaculture may help meet rising demand for fish protein globally. The alternative proteins sector is experiencing high growth and so may increase demand for seaweed- and algae-derived products (Byrne 2017; Fleurence et al. 2018). Novel technologies in food production aim to increase food security, but their use must be thoroughly evaluated for safety in the food chain. Acceptance can be affected by consumer perception of new technologies compared with more conventional farming methods.

Studies have shown that some human-made contaminants can be found at higher concentrations in farmed fish than in wild fish (Justino et al. 2017), which may indicate a need for additional regulation and surveillance of aquaculture products. A shift from wild capture to aquaculture production of fish may

also affect levels of food fraud, with farmed fish increasingly becoming substituted for marine fish (Reilly 2018). If novel technologies reach the point where there is scientific consensus that they are safe and beneficial, consumers will need to be informed about their use and consequences in a clear, balanced and accessible manner.

3.2.2. Alternative proteins

Alternative proteins are sustainable or non-animal substitutes to conventional animal-based protein sources. Consumers may switch to alternative proteins for perceived health benefits (IRI 2017), for ethical reasons (Hancock 2017), or to reduce environmental impacts (Alexander et al. 2017; European Commission 2016). Alternative proteins are expanding from predominantly plant-based to include other non-conventional, animal sources, such as insects, and laboratory-cultured meat products. An alternative protein source may be deemed a novel food if it has not been widely consumed by people in the EU before May 1997 (FSA 2018b).

Key issue: natural alternatives

Animal-based protein sources are increasingly viewed as unsustainable, in particular cattle raised for beef production, due to high emissions of carbon dioxide and methane (Gerber et al. 2013). Replacing half of all animal protein eaten worldwide with insect sources could cut farmland by a third and substantially decrease greenhouse gas emissions (Alexander et al. 2017). However, there are challenges with scaling up production and consumer acceptance in the UK market.

- **Insects** are considered a more sustainable source of protein than prevailing animal sources, potentially as much as soybean-based products. They are commonly consumed in parts of Africa, Asia and South America, but UK consumer acceptance of insects as a food product is low (Tao & Li 2018). The introduction of insect protein through 'insect flours' is providing an entry point (Morrissy-Swan 2018), as is the use of insects as animal feed (Makkar et al. 2014; Van der Fels-Klerx 2018).
- **Jellyfish** are also consumed in non-Western cultures, and could provide a healthy and sustainable source of animal protein to the UK (Mitzman 2017; Petter 2017). However, as with other marine species, there are growing concerns about the presence of microplastics in jellyfish (Macali et al. 2018).

Key issue: cultured proteins

Advances in tissue engineering and synthetic biology have enabled the production of animal proteins in laboratories rather than farms. The emerging 'cultured' protein industry has potential to capitalise on current consumer preferences for sustainable, ethical and healthy food. However, UK consumers still have some significant concerns about the technology (Bryant & Barnett 2018); more broadly, food naturalness is a high priority for consumers (Román et al. 2017).

- **Cultured meat** is produced by cultivating animal cells *in vitro* (Bhat et al. 2017). The technology has potential for producing the animal proteins UK consumers prefer in a more sustainable and ethical way, although further research will be required to fully replicate the diverse tastes and textures of natural meat (Bomgardner 2018). Cultured meat has been claimed to offer health

benefits through altered nutritional content and reduced exposure to potential contaminants, and because it helps combat antimicrobial resistance through reduction of antibiotic use in animal husbandry (Bhat et al. 2015; Lhermie et al. 2017).

- **Cultured milk** is created by genetically modified yeast that produces milk proteins. It is possible to make cultured milk that has the same nutritional value and taste profile as traditional milk (New Harvest 2017), but without the related emissions of carbon dioxide and methane or exposure to bacteria and growth hormones.

Relevance to UK food systems

The alternative proteins sector is already growing, but it remains to be seen whether sustainable animal alternatives and cultured proteins will be embraced by consumers. However, as consumers are increasingly demanding healthy, ethical and sustainable food products (Burrows 2017; IPSOS Knowledge Centre 2018), there is a real opportunity for alternative proteins to disrupt the market. The research conducted for this study suggests that, if cultured meat and milk were to become a major part of the UK diet, repercussions could be felt along the entire meat and dairy supply chains.

Existing food labelling practices may need to be revised if insect-derived products, such as 'insect flour' become more prevalent. There are concerns that cross-reactivity between edible insects and other allergens (such as crustaceans) may be clinically relevant (Van Broekhoven et al. 2016; Ribeiro et al. 2018). A similar challenge is posed by cultured meat and cultured milk products. Consumers may also want information about the technologies behind cultured proteins and the scientific consensus regarding safety. Food fraud – in this context, where products are sold as cultured when they are animal-derived, or vice versa – may pose a new threat to food authenticity. There may be contamination challenges associated with laboratories producing cultured products as well, but the food industry already has high-tech production facilities that are kept to an appropriate standard, many of which are laboratory quality.

3.2.3. Consumers

Food systems are changing from supplier- to consumer-driven. Increasingly active consumers influence food producers, manufacturers and retailers to deliver the products they want, in the way they want (Halberg 2017).

Key issue: changing demands

The following trends demonstrate that consumers have a wide range of heterogeneous demands and concerns which they enforce through purchasing power. Food systems will be challenged as a result of the more segmented market demand.

- **Healthy eating** is increasingly on consumer agendas, and younger consumers in particular are willing to pay more for products that they consider as healthier (Nielsen 2015; PricewaterhouseCoopers 2017). Perceived healthier attributes include freshness, minimal processing, vegetarian, vegan, gluten free, natural and organic. Consumer-perceived health benefits are sometimes, but not always, supported by evidence (Ciacci et al. 2014; Dangour et al. 2009; Niland & Cash 2018).

- **The sustainability and ethics** of food production are of growing concern to consumers (PricewaterhouseCoopers 2008), who are paying more attention to issues related to environmental sustainability and animal welfare (Defra 2011). Workshop participants and several interviewees also highlighted the importance of this trend. These concerns can manifest in dietary choices, such as vegetarianism (Public Health England and FSA 2014) and veganism (Vegan Society 2016 [survey conducted by IPSOS Mori]), as well as product choices, such as organic, alternative protein or, potentially, cultured meat and milk.

- **Consumer trust** in food in the UK is understood in a variety of different ways. The 2018 Biannual Public Attitudes Tracker (FSA 2017a) found that there were high levels of trust and engagement with food safety: 41 per cent of the population trust that the people who produce and sell food have their best interest at heart; 59 per cent trust that those who produce and supply food ensure that it is safe, honest and ethically approved; 60 per cent trust that the food industry is fairly regulated; and 73 per cent trust the authenticity of ingredients, origin or quality of food. Another survey found that consumer trust in the UK food and grocery sector has risen overall, from 50 per cent to 59 per cent, in the period 2012–2018 (Which? 2018). High-profile food fraud cases, such as the horsemeat scandal in 2013, however, contribute to periodic drops in consumer confidence (Which? 2013). Such approaches as data sharing, transparency, labelling and assurance schemes have a role to play in building and maintaining consumer trust.

- **Changing demographics** within the UK include an ageing population and increasing ethnic diversity (ONS 2011, 2017). Associated changes in consumer priorities could impact the food industry through redirection of purchasing power and changes in the origin and type of food imports. Additionally, several interviewees and workshop participants noted that economic growth in middle-income countries is predicted to lead to a continued demand for meat products (see also Godfray et al. 2018). Workshop participants and several interviewees also emphasized that this demand will likely have environmental consequences, as well as potential impact on the UK through the effect on international trade.

- **Convenience** is expected throughout the stages of the supply chain that consumers interact with. Purchasing channels have expanded to include online shopping (McKevvit 2017) and food delivery companies (NPD Group 2017); both sectors are growing in value year on year. Food delivery companies, however, may be different from traditional food companies in terms of culture, priorities and approaches to regulatory compliance. Several workshop participants and interviewees noted that demand for convenience is also affecting food formulation and packaging, as consumers seek to eat on-the-go from flexible, resealable packaging incorporating convenient features, such as pouring spouts (Business Wire 2017; Skoda 2017).

Relevance to UK food systems

There are aspects of changing demand that are in tension with each other. Reducing plastic packaging (Defra 2018), decreasing food waste (WRAP 2017) and increasing convenience are examples of conflicting demands. As the food industry attempts to meet this challenge, new packaging and food formulations may enter the market.

Workshop participants observed that, if consumers more widely use all available purchasing channels, the expectation of choice will likely grow. Consumer demand for information may lead to brands becoming more accountable for their production and manufacturing practices (Cooper 2017) and to generally greater transparency in the UK food system.

While it is estimated that up to 1 per cent of the UK population has coeliac disease, a lifelong condition for which the primary treatment is a gluten-free diet (West et al. 2014), gluten-free demand is growing disproportionally among consumers in general due to perceived health benefits (Munday & Bagley 2017). As a result, gluten-free food options are more than four times the cost of non-gluten-free foods (Burden et al. 2015), placing an economic burden on coeliac sufferers. Furthermore, there are potential unintended health consequences of consuming gluten-free food due to formulations having different nutrition profiles to conventional alternatives (Fry et al. 2017).

Several interviewees observed that, as producers, manufacturers and retailers move to meet consumer demands, they may follow new practices and processes, develop new formulations and use new packaging materials, all with potential food safety implications. New production and manufacturing processes may involve stages vulnerable to microbial or chemical contamination, reformulations could affect shelf life, and new packaging components could leach into food products or change microbial risks. Consumers will also need more accessible information as the range of alternative products grows, which could include food origin, production and/or transport method, nutritional profile and packaging type.

3.2.4. Contaminants

Contaminants are substances that have not been intentionally added to food. These substances may be present in food as a result of the various stages of its production, packaging, transport or holding that generally have a negative impact on the quality of food and may imply a risk to human health (European Commission 2018a). Such substances can enter the food chain at multiple points, including production, processing, transportation and storage. This brief relates to both chemical contaminants – such as heavy metals and metalloids, mycotoxins, persistent organic pollutants, and acrylamide (Rather et al. 2017) – and microbiological contaminants (Bhunia 2018).

Key issue: identification
With the increased industrialisation of the global food supply, and especially with pressures to meet growing demand, researchers are continually identifying new contaminants and exploring how they may affect the food system and human health (Milner & Boyd 2017; Ng & Von Goetz 2017).

- **Novel analysis methods** are emerging that may offer advantages over conventional techniques. Biosensors combine the selectivity of biological systems with the processing power of modern optoelectronics (Jha 2016), for example a nanomaterial-based optical aptamer assay has been developed that offers fast and highly sensitive detection of contaminating chemicals (Lan et al. 2017). Microfluidic paper–based analytical devices (μPADs), may also provide a rapid, easy to use and low-cost approach (Hua et al. 2018).
- **Rapid detection methods** could enable food handlers and consumers to test food for contamination at the point of use. A surface-enhanced Raman spectroscopy (SERS) method has been developed that can use an adapted smartphone to detect low levels of bacterial

contamination (Pearson et al. 2018). Similar point-of-use analysis tools could complement existing monitoring along the supply chain to provide end-to-end monitoring capabilities.

Relevance to UK food systems

Food products are exposed to a wide array of chemicals, both intentionally and unintentionally. Maximum residue levels (MRLs) for pesticide residue are reconsidered at renewal points to ensure that the latest scientific research is taken into account (European Commission 2018b). Delays in responding to new knowledge can place consumers at risk. The unintentional risk of chemical contamination is also a persistent threat. As primary and secondary industries[3] evolve, they may generate new waste products that enter the environment and, potentially, food products. Changes to regulations in response to such events can occur slowly, leaving consumers vulnerable in the intervening period. Safeguarding against microbiological contamination will continue to be crucial for UK food systems. These issues are compounded by the geographical spread of food systems, which presents difficulties in ensuring that regulations regarding contamination are consistently enforced.

Research and surveillance are necessary to prevent chemical and microbiological contaminants from entering the food chain and potentially harming consumers. Acceptable levels of contaminants in food need to be kept up to date and based on the latest scientific evidence. It may be challenging for UK agencies to meet the growing task of regulating for and monitoring contaminants with their available resources and increasing responsibilities following the UK's planned departure from the EU.

3.2.5. Synthetic biology

Synthetic biology is an emerging field that involves using engineering principles to design and build biological systems and tools for useful applications. The field has been enabled by advances in DNA (deoxyribonucleic acid) synthesis, DNA sequencing and computational power. In the past few years, new genome engineering tools have been developed that enable scientists to alter, add or remove genetic material from an organism with near-complete precision. With these new tools, genetic manipulation can be performed more quickly and more accurately than ever before.

Key issue: precision editing

Altering genetic material has historically been an expensive and uncertain process, but modern genome engineering techniques are relatively cheap, powerful and precise (Song et al. 2016; Wadha 2015). Furthermore, their use is better guided by the growing understanding of genomes. Perceptions and regulations around genetically modified food predominantly focus on 'transgenic' crops – made by inserting genetic material from one species into another using non–precision editing approaches – rather than modern precision editing technologies.

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[3] Primary industry refers to industries involved in the production of raw materials. Secondary industry '(1) takes the raw materials supplied by primary industries and processes them into consumer goods, or (2) further processes goods that other secondary industries have transformed into products, or (3) builds capital goods used to manufacture consumer and nonconsumer goods' (Britannica 2018).

- **Precision genome editing** is now possible, for instance, with CRISPR/cas9, ZFN or TALEN systems (Davies et al. 2017; Haque et al. 2018; Van Eck 2017). (CRISPR stands for clustered regularly interspaced short palindromic repeats; cas9 stands for CRISPR associated protein 9; ZFN stands for zinc finger nucleases; and TALEN stands for transcription activator–like effector nucleases.) The changes effected by these systems are 'subgenic' rather than 'transgenic'; that is, they alter an organism's genetic material directly, in a defined manner (Sticklen 2015). As subgenic alterations could occur naturally, they are not deemed to fall under GM regulations in some jurisdictions (Waltz 2016). However, the current EU position is that gene edited crops are encompassed by existing GM legislation (CJEU 2018; EU Scientific Committees 2014). The field is still emerging, so there is no guarantee of widespread commercial success. In addition, there is active debate regarding unintended, off-target effects (*Nature Methods* Editorial 2018) and the feasibility of regulating a process in which no traces of the editing might remain in the organism (Carroll & Alta Charo 2015).
- **Higher yielding and robust** food producing organisms are a key goal of genome editing in food systems. Making organisms more robust towards pathogens and harsh environments could help improve food security in a changing environment (Song et al. 2016).
- **Gene drives** based on genome editing systems can propagate genetic elements through a population. There is potential to use gene drives as a form of pest control in an agricultural setting (Courtier-Orgogozo et al. 2017), which could reduce pesticide use and improve food safety. However, the long-term risks of introducing gene drives into the environment are not yet known.

Key issue: crop protection

Fundamental research into novel ways of controlling crop pests could help improve food security and reduce contamination, though such research is currently at an early stage.

- **Nucleic acid vaccines** are a synthetic biology approach being developed to protect crops from pathogens (Niehl et al. 2018). Unlike pesticides, which can harm non-target organisms, lead to resistance and accumulate in the environment, nucleic acid vaccines have high target specificity and degrade rapidly in water and soil (Dubelman et al. 2014).

Relevance to UK food systems

Genome editing may help ensure future food security for the UK through the generation of high-yield, disease-resistant and hardy crops and, potentially, animals. Consumer opinion on GM foods fluctuates, with approximately a quarter of people in the UK having concerns about GM products (FSA 2017a). Unlicensed or unregulated genome editing could lead to a new aspect of food fraud – 'genetic food fraud' – whereby distributors and consumers are not correctly informed about the genetic provenance of produce. Incidents of this nature could erode UK consumer confidence in genetically engineered food and in the food sector more broadly. Regulation for safe use and MRLs (if appropriate) will be needed if nucleic acid vaccines emerge as an efficient and practical alternative to pesticides.

Informing consumers about the genetic status of their food may become more important, both through educational outreach and through labelling approaches. Surveillance and monitoring practices may need

to evolve to meet new challenges of identifying not just the species of origin, but also whether the species has undergone (un)regulated genome engineering. Employing up-to-date biosurveillance[4] and digital processes, along with a workforce skilled in the disciplines of genomics and bioinformatics, may help to meet these challenges. Developing and maintaining this genetic surveillance infrastructure and skilled workforce will in itself be a challenge.

3.2.6. Genomics

An organism's DNA can be read through a method called DNA sequencing, enabling exact identification of the organism and providing insights on its traits (Illumina 2018). Technologies used to read DNA have significantly increased in throughput (Bosch & Grody 2008; Illumina 2018) and decreased in cost (Wetterstrand 2018) over the past decade.

Key issue: tracking and surveillance
With the increased throughput and decreased cost of DNA sequencing it has become routine to read DNA. DNA can be isolated from organisms or food products at any stage of the supply chain and then rapidly tested for authenticity or safety purposes.

- **Identification of contamination** via DNA sequencing is rapid and specific, enabling identification of the exact microbial strain and helping locate disease outbreaks. Biosurveillance methods, such as pulsed field gel electrophoresis, serotyping and phage typing, are rapidly being replaced by whole genome sequencing and metagenomics approaches.
- **Identification of food fraud** will be aided by precise determination of food type and origin, regardless of whether processing – such as mincing or filleting – has altered the food's physical appearance.

Key issue: boosting production
DNA sequencing and genetic analysis methods can inform selection programs in animal husbandry, enabling increased production without the involvement of direct genetic modification.

- **Informing selective breeding** programs through identifying beneficial traits could leverage genomics advances without employing genetic engineering.
- **Understanding livestock microbiomes** – the complex community of microbes that live in animals' stomachs – may enable increased growth and milk production through optimised nutritional programmes (Steward et al. 2018).

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[4] Defined as the 'active data-gathering with appropriate analysis and interpretation of biosphere data that might relate to disease activity and threats to human or animal health—whether infectious, toxic, metabolic, or otherwise, and regardless of intentional or natural origin – in order to achieve early warning of health threats, early detection of health events, and overall situational awareness of disease activity' (NCBI 2011).

Relevance to UK food systems

Foodborne diseases affect producers and consumers, to significant economic and societal detriment (Tam et al. 2012; Tam & O'Brien 2016). Advances in surveillance, monitoring and detection approaches will help identify contamination more quickly and more accurately, thus helping to reduce the burdens caused by foodborne disease–related illnesses. The use of genomics to combat food fraud could strengthen consumer trust in food supply chains, by addressing consumer demand for knowledge, education and transparency so that consumers can make more informed decisions (FSA 2016). Sequence data from food products could form part of a wider traceability network if stakeholders throughout the food system were to interact openly with each other.

Maintaining up-to-date digital systems and capabilities, along with a workforce skilled in the disciplines of genomics and bioinformatics, can facilitate taking full advantage of genomic advances. Policy approaches can encourage businesses to share genomic data relevant to food safety and authenticity in order to increase transparency and agility in response to disease outbreaks.

3.2.7. Packaging and food waste

In the UK, an estimated £17bn of food waste occurs each year, while 2 million people are malnourished and a further 3 million are at risk of becoming so (Priestly 2016). As 85 per cent of food waste post-manufacture in the UK arises from consumers, the primary mechanism being used to tackle the issue is public education (WRAP 2017). For example, in partnership with the Department for Environment, Food and Rural Affairs (Defra) and the FSA, the Waste and Resources Action Programme (WRAP) has created new labelling guidance to give consumers the confidence to consume food for as long as is safely possible (Smith 2017). Emerging technologies may offer another approach to reducing food waste.

Key issue: shelf life

Food spoilage is a complex process whereby microbial, chemical or physical changes make food products unacceptable for consumers (Petruzzi et al. 2017). Food waste can occur when food spoils either before purchase or consumption. Increasing shelf life – the length of time before a food product spoils – can reduce food waste. Plastic packaging is a key method to increase shelf life but is currently a target for reduction due to environmental concerns and consumer demands (Defra 2018).

- **Biodegradable packaging** is being developed from milk proteins (Cottingham 2016), starch (Javed 2018), and plant-derived lipids (Apeelscience 2018). These materials offer the same benefits as plastic packaging – exclusion of oxygen and prevention of contamination – while meeting consumer demand for increased sustainability.
- **Active packaging** aims to combat food spoilage by absorbing gases, reducing humidity or absorbing UV energy (Wyrwa & Barska 2017). Emerging types of active packaging, such as active releasing systems, antimicrobial polymers, moisture scavengers and carbon dioxide emitters, can also exhibit antimicrobial or antioxidant properties (Yildirim et al. 2017).

Key issue: personalised food

One driver of food waste is the uncertain and fluctuating relationship between supply and demand. For example, retailers may suddenly stop purchasing a product due to reduced demand, leading to significant waste. Fresh food products with a short shelf life are particularly vulnerable to such effects.

- **Personalised food** that meets an individual's nutritional requirements and taste preferences and that has controlled texture and absorption properties could be created using 3D-printing technology, from long-shelf-life, powdered components (EurekAlert 2018). Existing 3D printing of food is only available as a prototype and is limited to components that can be extruded through a syringe (Yang et al. 2015). Manufacturers expect 3D food printers to become a common kitchen appliance in 10 to 15 years, but several high-end restaurants already use them to enhance presentation and conduct preparatory work (Chadwick 2017).

Relevance to UK food systems

Increasing shelf life could help address the food waste crisis within the UK, with both economic and societal benefits. However, the nature of how food is stocked, purchased and consumed is changing. Provision of food on demand from large, online order fulfilment centres could have an impact on packaging and shelf life requirements, as well as food waste. With consumer preferences currently supporting growth in the fresh foods sector (Euromonitor International 2018), novel packaging will have to be equal – if not superior – to plastic packaging at maintaining the appearance and sensory characteristics of fresh food. Novel packaging materials may play a role in the wider context of a drive to reduce the use of plastics within the UK food system. The safety and effectiveness of new food contact materials will need to be established. Biodegradable packaging made from biomaterials may be edible or in contact with food, which in certain circumstances could pose an allergy risk. For instance, packaging made from milk proteins (such as casein) could trigger allergic reactions in those with a dairy allergy. Therefore, appropriate regulation and control of novel packaging materials is paramount.

Individuals have different nutritional requirements, determined by age, sex, weight, physical activity and even their gut microbiome. Personalised food could help consumers meet their individual requirements and preferences. However, personalised food production could pose labelling challenges, as each product would be customised and so require a custom label. Automatic label generation at the point of creation or other approaches may be needed to ensure consumers are fully informed.

3.2.8. Sensing and data-driven decision making

Sensors are devices or systems capable of detecting and responding to an event. The response is most commonly through a human-readable output or transmission of data to a network. Sensors are needed throughout the food supply chain to improve efficiency and ensure suitable food quality.

Key issue: monitoring

Monitoring food quality is necessary throughout the food system, from harvest to home. Advances in chemistry and engineering are driving the development of new sensing technologies, which offer the opportunity to better monitor food products throughout the supply chain.

- **Smart packaging** has integral sensors that can continuously report on product quality. Sensors are being developed to measure food spoilage through changes in pH (Braskem 2017), detect microbial contamination through DNA probes (Yousefi et al. 2018) and test for fish freshness via volatile amines (Chang et al. 2017). Although some smart packaging tools are already available and readily used by businesses, the industry is still in the initial stages of growth (Deloitte 2018).

- **Edible probes** can be naturally occurring constituents of food or components added during processing. Researchers are investigating the photophysical properties of molecules that are 'generally-recognised-as-safe' and their potential for use as food quality and safety indicators (Corradini et al. 2016). Advances in ultra-thin, biodegradable and safe-to-eat temperature sensors could be applied to food products and wirelessly connected to a network, although researchers estimate that it will take from five to ten years for sensors safe for both human health and the environment to be developed (Salvatore 2017; Schaefli 2017).

Key issue: data-driven decisions

Food systems are dependent on unpredictable conditions, including temperature, weather conditions and markets. Responding slowly to changing conditions can decrease producers' productivity and increase food waste. Advances in sensor technology and connectivity are paving the way for more agile food systems.

- **Increasing connectivity** between sensors and downstream systems is possible due to advances in battery-powered wireless networks that can be deployed across the supply chain, including food processing plants and distribution networks (Jawad et al. 2017). Up-to-date and accurate data enable actors in the food system to make informed decisions. Data can also be fed into tools capable of synthesising multiple data inputs, for example, machine learning and artificial intelligence systems (Kamilaris & Prenafeta-Boldu 2018).

- **Drone-mounted sensors** can be rapidly deployed to measure plant health and disease, soil quality, and irrigation across large areas (Corrigan 2018; DOE & Lawrence Berkeley Laboratory 2018). Detailed real-time information could enable automated application of pesticides or fertiliser to a defined area of need, reducing levels of agricultural chemicals in food products and the environment.

Key issue: traceability and transparency

Traceability and transparency have become more prominent concerns in reaction to the 2013 horsemeat scandal (Agnoli et al. 2016; Barnett et al. 2016; Bates et al. 2018). Consumer demand for sustainable and ethical food has also triggered a need for the food industry to ensure the environmental, animal and human welfare provenance of food. Robust traceability systems that are transparent to consumers could increase trust in supply chains and support packaging claims relating to sustainability, ethics and global issues, such as place of origin, production method, global supply chains or fair trade (FSA 2016).

- **Blockchain** or distributed ledger technology (DLT) can potentially offer a secure and transparent method of supply chain management along the entire supply chain (Tripoli & Schmidhuber 2018). The manner in which transactions are stored may provide protection against accidental or purposeful future alteration. While the technology is reliant on truthful data inputs, future

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integration with sensors in production, processing and distribution facilities could make it challenging to falsify inputs. However, the emergence of non-interoperable DLT/blockchain, implementations leading to a fragmented ecosystem, as well as its possible high energy consumption, are among some of the challenges that can potentially limit its widespread adoption (Deshpande et al. 2017). Blockchain is still considered an immature technology, with meaningful commercial scale estimated to be achieved in three to five years (Carson et al. 2017).

Relevance to UK food systems

Advances in monitoring processes can help ensure that food is safe for consumers to eat, for example, by reducing residual pesticide levels in food products, and help reduce food waste in the supply chain. Sensor-generated data may be fed into food traceability networks that can combat food fraud, which would help authorities guarantee food safety and authenticity and thus raise consumer confidence.

There is an opportunity to participate in the development of a connected, data-driven food supply chain from the farm gate to the consumer. Regulation and standards can help to ensure businesses are sufficiently transparent and share appropriate data with authorities and the public. As the food supply chain evolves, existing regulation, surveillance and monitoring approaches may be reconsidered. Consumer safety will be a consideration with respect to any changes in these areas. The FSA is already trialling the use of blockchain as a regulatory tool for compliance in the UK (FSA 2018a) and has the opportunity to lead the way on the use of technology to increase traceability and transparency.
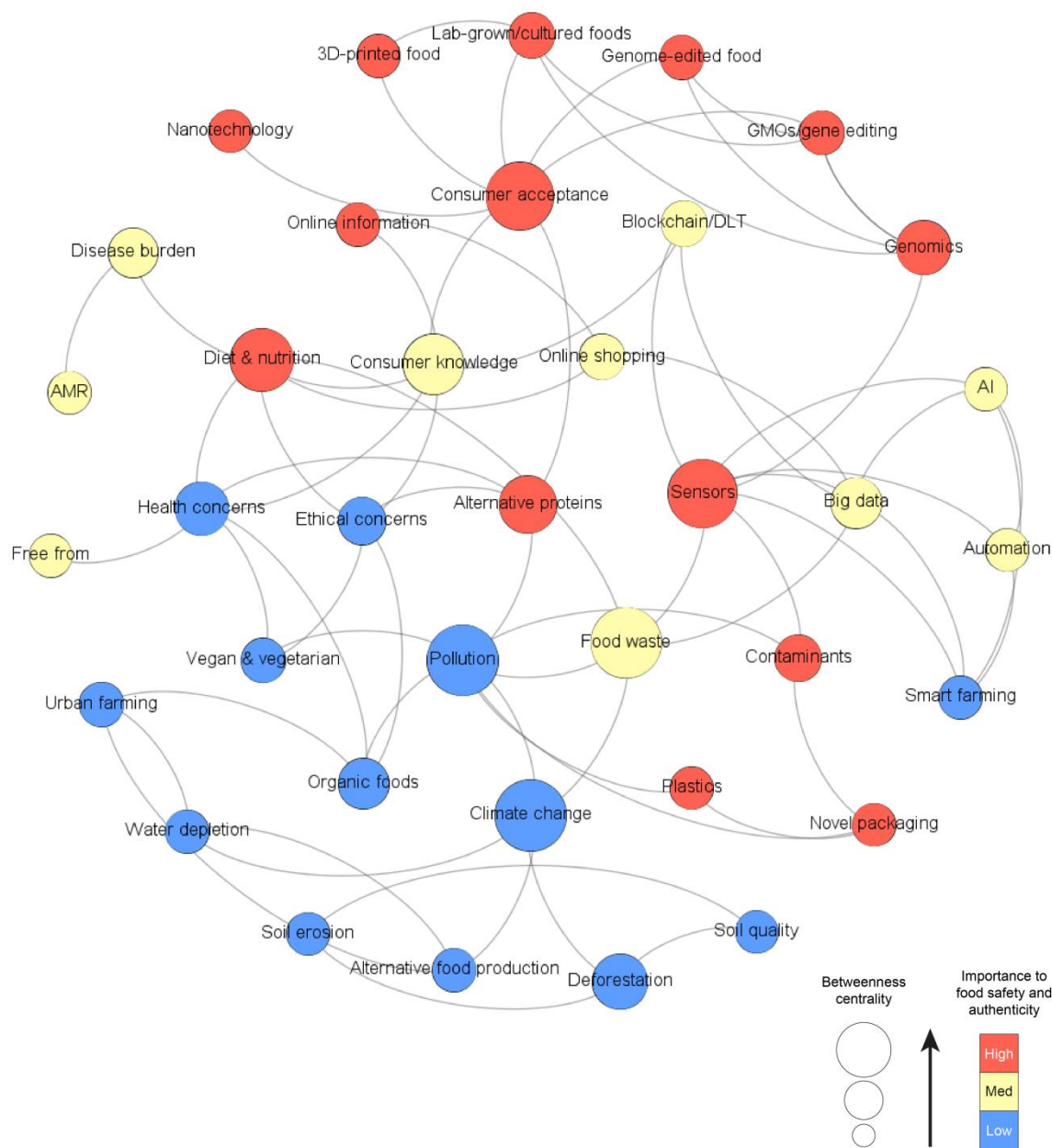
3.3. Mapping systemic interdependencies

Food systems are complex systems that are, in turn, interdependent with other complex systems, such as health, energy, climate and agriculture systems, comprising many actors, relationships and processes as well as difficult-to-predict events. We sought to develop a visual representation that captured this complexity, but that was capable of conveying information 'at a glance'. Figure 3 introduces a map of systemic interdependencies illustrating the issues presented in the global food systems map (Figure 1). Themes presented in the global food system map are represented in this network as nodes, which are based on an understanding of the food system gathered through desk research and expert interviews, and which have been connected by the study team and in discussion with the FSA. Political themes have been excluded due to their broad influence across the entire food system map.

Gephi[5] was used to calculate the 'betweenness centrality' of each theme/node and to scale the node size accordingly. Betweenness centrality measures the number of times a node lies on the shortest path between other nodes, thus indicating bridging themes that may be influenced by – or influence – many other issues (EMBL-EBI 2016). These bridging themes have a strong influence within the network because they control any information passing over to other themes. The betweenness centrality indicates the importance of certain themes in influencing the flow of information between the nodes (Newman 2005). Additionally, the direct importance of themes related to food safety and authenticity was scored on a scale of one to three by the project team during two rounds of discussion. The scores were adjusted through further discussion with the FSA in relation to the relevance of the theme in respect of the agency's remit. The highest score, of three, is represented in red; two, with yellow; and one, with blue. Future versions of the map of systemic interdependencies could offer additional value by weighting the directionality of interaction between the issues, supporting analysis of how changes, stresses or shocks at one point are felt throughout the system.

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[5] Gephi version 0.9.2. An open source network analysis and visualisation software package.

Figure 3: Map of systemic interdependencies

Source: RAND Europe analysis

The map of systemic interdependencies serves as a tool to help place specific issues in the context of a wider food systems network and to quickly identify pathways through which they could have an impact on food safety and authenticity. The map could also help explore potential cascading impacts, where a shock or solution to one issue may have wider repercussions to neighbouring and even distantly related issues. This representation was tested during an expert workshop, where it helped attendees place their expertise in the wider food system and stimulated discussion. Additionally, the map of systemic interdependencies exemplifies an approach to identifying issues that may become 'flash points' for the FSA in the future. Nodes which are red (within the FSA's remit) and large (highly interconnected) might

be candidates for more focussed monitoring. As part of ongoing foresight activities, the concepts of betweenness centrality and importance to food safety and authenticity could together form part of an information-rich dashboard of key issues to help strategic decision making.

3.4. Charting a course to an idealised food system

Having identified emerging issues and challenges for global food systems, we sought to develop a framework to support ambitious thinking aimed at meeting the challenges and seizing opportunities. Our framework does not present an exhaustive set of challenges, tools and goals, but, rather, aims to challenge stakeholders to consider how existing and emerging tools could be used to reach an idealised food system.

The framework in Figure 4 displays eight major challenges, including climate change, food waste and nutrition that have a strong bearing on the global food system and so are worthy of consideration. These eight challenges are not all directly addressable by the FSA, or even by a single country. The framework presents a set of tools and approaches that could be taken to address these challenges, with some specific examples given for each. The tools were identified during the earlier horizon scanning and expert interview stages of the study. We suggest three waymarks that could be important for reaching the ultimate goals of an idealised food system. We believe that reaching these waymarks would indicate significant progress towards food systems that are safe and authentic, affordable and healthy, sustainable and ethical, and resilient and adaptable.

In the following sections, we elaborate on the key challenges identified in the framework as well as the waymarks of the considered consumer, a supportive system and a receptive industry.

Figure 4: Pathway from the challenges currently facing the global food system towards the goals of a food system that is safe and authentic

Challenges
- Climate change
- Consumer trust
- Food waste and packaging
- International trade
- Nutrition
- Provenance & traceability
- Skills & workforce
- Technology acceptance

Tools & Approaches

Communication
- information
- education

Governance
- integration
- regulation

Changing practices
- dietary shift

Technology
- genetics
- sensors

Data-driven decisions
- AI
- Blockchain / DLT

Waymarks

Considered consumer
- informed
- selective
- healthy

Supportive system
- one health
- equitable
- cross-government

Receptive industry
- responsive
- values-driven
- profitable

Goals

Products
- Safe and authentic
- Affordable and healthy

Processes & systems
- Sustainable and ethical
- Resilient and adaptable

Source: RAND Europe analysis

3.4.1. Challenges

In this section, we briefly discuss each challenge facing the global food system in turn, outlining some key features and potential impacts on the UK food system.

Climate change

Climate change is driven by many factors, including the burning of fossil fuels for energy, deforestation, agriculture and industrial manufacture. Food systems contribute 19–29 per cent of global greenhouse gas emissions and 56 per cent of non-CO_2 emissions, such as methane, with livestock emissions alone responsible for 14.5 per cent of global greenhouse gas emissions (Vermeulen et al. 2012). According to workshop participants and interviewees, unchecked climate change could have serious impacts on food production, some positive (longer growing seasons in some regions) but most negative (increased frequency of droughts and heat waves, extreme and unpredictable weather, rising sea level). Climate change will impact food systems primarily through affecting food production. If average global temperatures continue to rise, workshop participants and several interviewees warned, the chance of synchronous shocks to the food system is predicted to rise significantly. An example of such an event would be the occurrence of multiple 'bread basket' (regions that provide large quantities of cereals, often due to advantageous soil types and climates) failures, which would lead to rapid price increases and food shortages. Workshop participants and a third of interviewees highlighted that in the most extreme cases this can lead to civil unrest and further disruption of food production. However, even for countries able

to absorb the financial shock, there may be a need to import from new countries to meet demand, which could introduce new health, safety and regulatory risks.

Consumer demand for more sustainable food systems may force the food industry to go beyond solely reacting to climate change and take a more active approach to addressing such issues as greenhouse gas emissions, food miles, decreasing biodiversity and decreasing soil quality. As new production and processing methods are introduced to meet this demand, there may be associated changes in the potential microbiological and chemical contaminants present in products. This would necessitate a review of existing standards and monitoring and enforcement practices.

Consumer trust

UK consumers currently have low trust in supply chains, especially international supply chains (FSA 2016), despite imports representing half of UK food consumption (Defra 2017b) (Section 3.2.3). The challenge is not just to rebuild consumer trust, but to maintain it through future stresses and shocks to food systems. While trust takes time to develop, it can be rapidly lost through food safety and authenticity scares, inaction or poor communication and engagement with consumers. Additionally, when a food safety or authenticity issue occurs, consumers often lose trust, not just in a brand, product or retailer, but more, broadly, in the entire food system (De Vocht et al. 2013). Restoring trust can also be more costly than managing the risks (Food Foundation 2016). If industry stakeholders and government agencies do not have consumer trust, they will be unable to effectively communicate with consumers, making it more difficult to address other key challenges.

Food waste and packaging

Food waste results in economic loss, environmental damage and social tension, in addition to threats to food security. Addressing food waste may involve informing consumers, improving industrial and retail processes, and devising ways to gain value from waste products. Workshop participants highlighted that efforts to reduce waste will require consumer acceptability and may introduce new food safety challenges – for example, repurposing or transforming unsaleable material into commercial products may not appeal to some customers and could introduce traceability concerns.

There is a tension between simultaneously reducing food waste and reducing the environmental impact of packaging material. The move towards reducing plastic packaging may lead to unintended side effects, such as increasing both food waste and safety risks from contaminants. Novel packaging could be introduced to replace plastics, but vigilance would be needed to ensure the materials are compatible with food contact material requirements. Harmful effects on human health related to food packaging materials can take time to emerge and understand. For example, the prevalence of micro- and nanoplastics in food and beverages – and their health and safety implications – requires substantial further investigation.

International trade

Workshop participants and several interviewees observed that, because the UK imports more than half of its food, geopolitical events and their repercussions for international trade could have a significant impact on the UK food system. For example, following withdrawal from the EU, the UK will need to define its own standards for foods produced and consumed in compliance with WTO and Codex Alimentarius rules and guidelines, and ensure that there are corresponding capabilities to monitor and enforce these

standards. This will require mobilisation of sufficient and high-quality scientific and other resources within the UK, where these resources were previously shared across EU member states. As the UK develops trade agreements with other countries, it will need to establish equivalence of standards. Additionally, UK vulnerability to international food systems shocks will require special attention in a trade context. These events could result in price increases or in products becoming unavailable, particularly in the short term.

Nutrition

The UK is facing a rising incidence of non-communicable diseases affected by nutrition, such as obesity (NHS Digital 2018), diabetes (Diabetes UK 2018), and food-related cancers (Cancer Research UK 2018) – a set of trends also discussed by workshop participants and several interviewees. This is a complex challenge involving a wide range of factors and stakeholders. Among these factors, food plays a major role, one that cannot be overlooked. The estimated cost of malnutrition[6] is high, at almost £20bn per year in England alone, representing 15 per cent of overall health and social care costs (Elia 2015). The costs related to obesity are estimated to be £6bn to the NHS annually (Dobbs et al. 2014; Tovey 2017). There are also challenges related to food products that have altered nutritional profiles through reformulation or that are novel to UK retailers. Novel foods may need focused surveillance until their provenance is trusted, and consumers may need to be informed of the altered nutritional content of reformulated foods to reduce the incidence of unintended consequences due to diet-related illnesses (Fry et al. 2017).

Provenance and traceability

The limitations of current food supply chains have been illuminated by such events as the 2011 *E. coli* outbreak (EFSA 2012) and the 2013 horsemeat scandal (EFSA 2013). Workshop participants, as well as a third of interviewees, emphasised that building systems and processes to enable better traceability of food as it flows through supply networks is necessary to meet the challenge of food safety and authenticity, as well as to ensure consumer trust. A skilled workforce, particularly in the disciplines of genomics and bioinformatics, will also be needed to underpin these developments. As the importance of food provenance to consumers grows, the food industry will be increasingly challenged to trace where and how products were made. Given the complex and international nature of supply chains, there is also a challenge to harmonise approaches across jurisdictions with differing regulations and levels of infrastructure.

Skills and workforce

According to workshop participants and interviewees, there is a significant and growing skills gap between expected knowledge and skills related to the production of safe and legal food, in both the food industry

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[6] Defined as 'deficiencies, excesses, or imbalances in a person's intake of energy and/or nutrients. The term malnutrition covers two broad groups of conditions. One group is undernutrition, which includes stunting (low height for age), wasting (low weight for height), underweight (low weight for age), and micronutrient deficiencies or insufficiencies (a lack of important vitamins and minerals). The other group is overweight, obesity and diet-related non-communicable diseases (such as heart disease, stroke, diabetes, and cancer' (WHO 2016).

and the enforcement community. Nearly half of interviewees, as well as workshop participants, highlighted the challenges facing certain sectors within the food industry that are experiencing a lack of appropriately skilled workers. One possible reason for the skills gap, mentioned by several interviewees, is a lack of investment by government and industry stakeholders in training and education of people with the required skill sets. Another reason suggested by an interviewee is the perception of the food industry as a 'low-tech' industry, which might discourage qualified graduates from entering the field. According to one interviewee, digitisation of the food industry is likely to increase over the next decade, due to both technology progression and a change in company leadership from 'digital foreigners' to 'digital natives'. As a result, significant upskilling may be required due to the replacement of some segments of the workforce with automation and robotics.

Technology acceptance
Technology cannot solve all the problems of the global food system, but there are certain challenges that can be met through its exploitation – for example, drought-resistant plants may help alleviate certain challenges associated with climate change (Song et al. 2016). However, workshop participants noted that consumer acceptance is an absolute necessity for any benefits to be realised. For example, GM products and food irradiation have both faced strong backlash from consumers and regulators that greatly reduced the presence and utility of the technologies, particularly in Europe.

3.4.2. Pathways to waymarks

To address these challenges, we propose using the tools and approaches to reach the three waymarks – of the considered consumer, a supportive system and a receptive industry – which we consider important to developing an 'idealised' food system that is safe and authentic (Figure 4).

Considered consumer
The considered consumer is informed, selective and healthy. There are a number of mechanisms that can help us mould today's consumers towards this ideal. Clearer communication, in the form of jargon-free and easily accessible information available on relevant government body websites, as well as educational modules on relevant food systems issues, eating habits and food labels in schools, could encourage healthy behaviours. Such behaviours could, in turn, lead to long-term changes in diet and consumption habits. Data-driven decision making tools and other types of technology can help consumers act on their knowledge through creating improved food information systems that detail every aspect of the food item they are about to purchase. These technologies could include using sensor technology to better survey production procedures and trace origins, helping consumers weigh the costs and benefits of consuming a certain product at a given quantity.

Supportive system

The supportive system adheres to 'one health' principles[7] and is equitable and cross-governmental. To move closer to this system, relevant public decision making bodies at the local, regional, national and international levels can base regulatory and other types of decisions on the ultimate objective of reaching an optimal health outcome for people, animals and plants, as well as their shared environment. In doing so, public officials can also consider how their actions affect the most disadvantaged members of society and ensure that structures and mechanisms are in place to help these citizens achieve healthy food consumption as well. Decision makers could ensure that all public bodies involved in matters of food production and consumption share their expertise and use their respective strengths to solve problems in a coordinated manner, avoiding a silo mentality. This joint effort would allow for issues beyond the FSA's purview to be tackled – including addressing non-communicable diseases – and also highlight which issues are not currently being addressed.

Receptive industry

The receptive industry is responsive, values-driven and financially sustainable. It adapts to changing consumer preferences or government regulation using the best technologies at its disposal. As illustration, this adjustment could take the form of a supermarket chain choosing suppliers with low ammonia emissions techniques for the production, storage and spreading of manure.[8] A supermarket chain could, for example, use sensors to oversee the production of their goods; if the sensors measured a higher than average level of ammonia emissions, the supermarket chain could decide to switch to suppliers with a low ammonia emissions policy as a result. While this action is a helpful first step, a receptive industry not only responds to the needs and requirements of consumers or government, but also actively deliberates and defines the values it wants its business model to reflect and its employees to uphold. This values-driven characteristic requires industry to think beyond responsiveness and lay a foundation for a constructive and proactive, rather than reactive, relationship with stakeholders. Lastly, a receptive industry would be financially sustainable while using technologies to grow its business in line with the values it has established.

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[7] Definition of the term one health from the US Centers for Disease Control and Prevention: 'One Health is defined as a collaborative, multi-sectoral, and trans-disciplinary approach – working at the local, regional, national, and global levels – with the goal of achieving optimal health outcomes recognizing the interconnection between people, animals, plants, and their shared environment' (CDC 2018).

[8] For more information regarding methods to reduce ammonia emissions, please see Guthrie et al. (2018).

4. Lessons learnt and recommendations for future foresight activities

This study established a baseline and acted as a pilot for foresight activities potentially implemented by the FSA. It provides an overarching assessment of the global food system, with associated novel and emergent food system themes and their associated trends, pressures and drivers. Themes of particular relevance to the FSA through to 2030 were identified.

In addition to the results of the study, there is also learning from the process undertaken. While undertaking the research, many of the stakeholders we engaged with suggested actions that the FSA (or sometimes the UK government more generally) could take to address emerging challenges to food systems and how addressing these challenges will have consequences in other complex systems. To capture these expert opinions, we present them in section 4.1. In section 4.2, we build upon these insights to reflect on how the FSA might implement ongoing foresight activities.

4.1. Learning from stakeholder engagement

The expert interviews and workshop identified suggested future actions the FSA and other national or international bodies can take to mitigate challenges and capitalise on opportunities in global food system developments. The UK will need to continue to engage in priority setting for the development of international food standards, guidelines and codes of practice through the Codex Alimentarius Commission (FAO and WHO 2018) The harmonisation of standards relevant to the food system – which include those influencing inspection, packaging and labelling – could facilitate international trade, particularly in a climate of regulatory divergence (Neuwirth 2015). However, regulatory variation could also operate as a basis for learning to improve regulatory design, by planning adaptive regulation and comparing outcomes across regulations (Wiener et al. 2017).

Where harmonisation is not yet possible, consumers would likely rely on data-driven technologies for supply chain transparency. Supporting development of these technologies would be a useful investment of resources. This may require the collection and curation of more supply chain and food properties data. The use of genomics to address food fraud could be particularly helpful, but the affordability of this approach and consumer demand for it would need to be considered.

Another important approach to consider for increasing consumer trust is communicating to the public, through public awareness campaigns or marketing, that it is impossible to achieve complete safety and authenticity. This will need to include information about the limitations of food production systems and

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what information new technologies can offer consumers. With respect to technology more broadly, given the financial costs and time associated with managing its unexpected societal effects, devising a structure for engaging with those developing technology can be beneficial; if undertaken early enough in the commercialisation process, engagement can mitigate any unwanted repercussions, as well as help the technology become more useable for food systems–related purposes.

Workshop participants observed that in a UK context the area of 'sustainable consumption' with respect to food does not yet lie in the remit of any government body ('sustainable production' is within Defra's remit) and could logically align with the FSA's objectives. Related to this, participants also suggested that the concept of 'responsible consumption' could be considered. In addition, although this study focused on foresight tools, techniques and approaches, learning from historical examples could create a complementary mechanism for future planning. The FSA's strategic evidence fund might be well placed to finance these types of studies.

4.2. Establishing foresight activities in the FSA

The FSA would like to increase its foresight capabilities and capacity in order to have an informed and integrated view of the global food system and the challenges and opportunities that may arise in the mid- to long-term future. In addition to establishing the processes to achieve this level of foresight, further efforts may need to focus on creating an agreed governance mechanism to respond to the findings of foresight activities. Setting up such a governance mechanism will require careful consideration of who participates and how, as well as more resources. To have an impact on strategic decision making, there may need to be engagement with topics beyond the day-to-day operational activities of the agency and cross-government interactions. A mechanism for managing the complexity of data would be helpful, as well as a mechanism for evaluation to reflect on what was learned from each exercise, in order to identify any future changes that could be made and to identify and amplify approaches for securing the benefits of the foresight approach as a whole.

We recommend continuing to use a systems approach in future exercises. A next step for developing a programme of foresight activity using a systems approach would be to undertake a preliminary assessment and characterisation of the interdependencies between issues within the food system and with other systems. The map of systemic interdependencies developed for this study would be a useful starting point, building on the research already conducted in the pilot exercise and following further validation from the FSA and stakeholders.

One recurring issue we encountered was the reticence of some participants to rank issues according to relevance and impact due to their complex relationships in the system; this made prioritisation of issues difficult. An alternative could be to employ a process similar to the one deployed by the Dutch government to rank risks to national security – the Dutch national risk assessment (Nationaal Veiligheidsprofiel). In the Netherlands, the risk priorities are decided upon by the government, but the assessment employ insights from policymakers, knowledge institutions, security regions, consultancy firms and academic bodies, to investigate which human-made and natural hazards may threaten Dutch society (National Network of Safety and Security Analysts 2016). The UK National Risk Register follows similar

principles, involving a broad, multistakeholder effort and using a set of predefined inclusion criteria for the final list (e.g. Cabinet Office 2017).

We propose that the FSA undertake continual horizon scanning activities as an outline program, to keep informed of emerging technologies and issues that could impact food systems over a ten year timeframe. Such a timeframe is near enough on the horizon to be of political relevance and to pose threats or opportunities to food systems that could be mitigated or capitalised on, respectively. Horizon scanning activities could involve monitoring of academic literature, policy developments and news aggregators, as well as consulting stakeholder and wider professional networks. By targeting these information streams, the FSA would be informed about cutting-edge technological developments, changing geopolitical environments and corresponding social responses. To gain insight on the scanning findings and help disseminate results, workshops could be held biannually or quarterly. These workshops would ideally include FSA representatives, as well as experts in a range of disciplines. The inclusion of 'agitators' or 'wild cards', who may offer unorthodox viewpoints and unconventional wisdom, would offer considerable value to such workshops, as they could challenge the pre-conceived notions of attendees.

A primary goal of each workshop would be to identify one to three key issues that would be further explored with a period of deep-dive research. For example, plastic packaging is widely used to increase product shelf life, but as we learn more about the effects of microplastics on the environment, such packaging is increasingly targeted for reduction. Consumer trust is an important issue that cross-cut many of the themes explored in this study, but there are many factors affecting trust in the food system; these factors could be explored in greater detail and potentially prioritised according to their potential to improve trust and the related costs involved in doing so. The deep dive analyses would take the work beyond theme identification at the systems level, moving towards understanding the nuances and operational details of the chosen issues as well as interconnections with other systems – referring to the interdependencies mapping exercise for guidance. In-depth follow-up of the initial horizon scanning would be important to reach a point where the FSA can make informed decisions and shape its future strategy to mitigate future threats and capitalise on opportunities. Each deep-dive could form a concise research brief for dissemination to relevant agency teams and policymakers, whether within the FSA or in the wider government.

An optional approach to make the FSA's foresight activities more accessible would be to create a dashboard of current and emerging issues, including metrics, scales and appropriate threshold levels for analysis. Using output from the workshops and deep-dives (such as expert scoring), each issue could be flagged for relevance and impact, for instance, with a visual, 'traffic light' system. Such an approach would enable wide dissemination of the FSA's foresight activities and help policymakers understand potential future areas to prioritise at a glance. The dashboard could also be developed to show where government responsibility lies for each issue, to help the FSA identify agencies to approach where cross-governmental action is needed.

The FSA has the opportunity to build on their existing surveillance methodology (which addresses short-term threats) and implement foresight approaches to gain insight into medium- and long-term threats and opportunities. Aligning these surveillance and foresight strategies could create a streamlined process, where issues identified in foresight studies could inform the surveillance topics of the future. As such,

keeping existing surveillance approaches in mind when implementing foresight activities could offer operational benefits. With strong surveillance and foresight capabilities, the FSA has the opportunity to ensure food safety and authenticity within the UK, lead a cross-government taskforce on food-related issues and play an international role in advancing food systems understanding.

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6. Appendices

6.1. Terms and criteria

Table 1 presents themes and specific search terms that we used as part of the horizon scanning exercise in Phase II. The search terms reflect those that might signal themes and issues of future interest (row 1), the global food system (row 2), the aims and remit of the FSA (rows 3–6), and the macro- and micro-themes identified in the global food systems map (rows 7–11, in blue). We combined search terms in the following ways during the scan:

  a. Terms from row 1 combined with row 2
  b. Terms from row 2 with a combination of rows 3–6
  c. Terms from row 2 with terms derived from the macro-themes identified in the global food map (rows 7–11).

Table 1: Horizon scanning search terms

	Theme	Search terms
1	Terms signalling potential future interest	Risk* OR issue*OR vulnerabilit*OR trend OR driver OR pressure OR issue OR opportunity OR threat
2	Global food system	Food OR "food system" OR "global food system" OR "food supply chain" OR "global food supply chain"
3	Regulation	Regulation OR "regulatory regime" OR "regulatory approach" OR "regulatory model" OR "regulatory strategy" OR "Brexit"
4	Safety	Safety OR standards
5	Authenticity	Authenticity OR trust OR transparency OR crime OR fraud
6	Consumers	"Consumer demand" OR Consumer* OR "consumer interests" OR "consumer benefits" OR "consumer knowledge" OR "Consumer behaviour"
7	Culture	"Ethical foods" OR veganism OR vegetarianism OR "Organic food"
8	Industry	Supply OR "Industry 4.0" OR "Smart farming" OR "Urban food production" OR contaminants OR plastics
9	Technology	"Novel food" OR "3D printed food" OR "Synthetic food" OR "Lab grown food" OR "alternative proteins" OR "online platform" OR "digital grocery shopping" OR "Big data" OR blockchain OR automation OR "artificial intelligence" OR nanotechnology OR
10	Environment	Sustainability OR "climate change" OR "Circular economy" OR Pollution OR deforestation OR "soil erosion" OR water depletion OR "food waste"
11	Health	Diet OR Nutrition OR "disease burden" OR "infectious disease*" OR "Antimicrobial resistance"

Source: RAND Europe

We present specific assessment criteria in Table 2 that were used to evaluate potential themes identified from the horizon scan during the prioritisation phase of the study. A foresight exercise has some inherent subjectivity, but we introduced objectivity into the assessment by using defined criteria and different people to undertake the assessments. The criteria include general categories, such as evidence authority, organisation authority, novelty factor, and the possibility of successful implementation, as well as specific criteria, such as applicability to the global food system and relevance to the FSA's mission (safety, authenticity, accessibility, transparency).

The criteria were used in Phase II scanning and were used again in the Phase III prioritisation of the study. For the scanning phase, the issues and themes that emerged from the literature review were ranked against the criteria listed in Table 2 by one of four researchers conducting the horizon scanning. A

ranking exercise was conducted for each theme or issue against a scoring scale of low, medium, and high. The rankings were tested and reviewed by team members who undertook the scanning exercise and any differences in scoring between the researchers was discussed and noted in the analysis. The themes and issues that had the highest scores following the horizon scanning exercise were further assessed in the prioritisation phase through the interviews and expert workshop.

Table 2: Assessment criteria for the evaluation of potential issues

Criteria	Definition
Evidence authority	Although each item found should be supported by more than one source, this criterion assesses the quality of the **best** source available (e.g. leading scientist, academic paper). It measures whether or not the best source is perceived to have expertise, high credibility and a wide following among its community of interest.
Authority of the people/organisation undertaking the work	The reported work needs to support the belief that the work done has adhered to a rigorous and systematic protocol in terms of either experimental technique, mathematical/statistical analysis or an unbiased and highly informed analysis of societal issues. It should be credible, with a good chance of being pursued to achieve the stated outcomes.
Impact	This denotes the level of disruptiveness expected from each theme or issue identified, agnostic of whether the issue will have positive or negative consequences for the UK food system or the FSA's remit.
Novelty factor	This is the degree to which the evidence presents new developments, data, analysis or conclusions relating to the subject at hand. This may be the identification of an entirely new phenomenon, or an alternative and challenging analysis of mainstream thinking on a well-established one. This is the 'wow factor test' in assessing horizon scanning material. An item which represents an entirely new idea or interpretation of information such that it would radically change the way things are done would be acceptable, even if the evidence underpinning it were weak.
Probability of successful realisation	This attribute rates the extent to which the issue is likely to occur and considers drivers for and barriers to the appearance of the issue.
Applicability to the global food system	This attribute rates the extent to which the issue is related to and could affect key elements within the food system.
Relevance to the FSA's mission (safety, authenticity)	This attribute rates the extent to which the issue is important for and actionable by the FSA.

Source: RAND Europe

6.2. Experts consulted for interviews and workshop

The individuals identified here have consented to be named in the report together with their affiliations.

Table 3: List of experts interviewed during Phase III of the study

Interviewee	Primary affiliation
Professor John O'Brien	FSA Science Council, Working Group Chair
Mr Michael Scannell	European Commission
Mr Mark Rolfe	FSA Science Council
Professor Tim Benton	University of Leeds
Professor Nicholas Watson	University of Nottingham
Professor Lenny Koh	University of Sheffield
Dr John Ingram	University of Oxford
Professor Ian Noble	Mondelez/N8AgriFood
Professor Susan Mitchie	University College London
Mr John Basset	Institute of Food Science and Technology
Professor Sir Charles Godfray	University of Oxford
Dr Jessica Fanzo	Johns Hopkins Berman Institute of Bioethics
Ms Judith Batchelar	Sainsbury's, board member of Environment Agency
Dr Marianne Ellis	University of Bath
Professor Corinna Hawkes	City, University of London

Table 4: List of attendees at the workshop held on 12 September 2018

Workshop attendee	Primary affiliation
Ms Sue Davies	Which?
Prof Francis Butler	University College Dublin
Ms Marie-Valentine Florin	International Risk Governance Center, École polytechnique fédérale de Lausanne
Dr John Ingram	University of Oxford
Dr Mukesh Kumar	University of Cambridge
Dr Andrew Hellewell	Biotechnology and Biological Sciences Research Council
Dr Beatrice Conde-Petit	Buhler
Ms Judith Batchelar	Sainsbury's, board member of Environment Agency
Dr Rachel Ward	Institute of Food Science + Technology r. ward consultancy limited
Mr Vincent Doumeizel	Lloyds Register
Dr Francesca Gauntlett	Animal and Plant Health Agency
Dr Wayne Martindale	National Centre for Food Manufacturing, University of Lincoln
Mr Mark Swainson	National Centre for Food Manufacturing, University of Lincoln
Ms Kerina Cheesman	Food and Drink Federation
Prof Lisa Jack	University of Portsmouth
Prof Lenny Koh	University of Sheffield
Durran Eden	Raynor Foods
Dr Jon Freeman	RAND Europe
Dr Elta Smith	RAND Europe
Ms Pamina Smith	RAND Europe
Dr Gordon McInroy	RAND Europe
Prof Norval Strachan	Food Standards Scotland, Chief Scientific Adviser
Dr Kasia Kazimierzczak	Food Standards Scotland
Ms Mary Quicke	Quicke's Traditional Ltd. FSA, board member
Prof Guy Poppy	FSA, Chief Scientific Adviser
Prof Alan Boobis	Imperial College London FSA, Committee on Toxicology, Chair
Prof David McDowell	University of Ulster FSA, Advisory Committee on Microbiological Safety of Food, Chair
Prof John O'Brien	The Food Observatory, Director FSA Science Council, Working Group 3, Chair

RAND Europe

Mr Mark Rolfe	Kent Scientific Services
	FSA Science Council
Prof Patrick Wolfe	University College London
	FSA Science Council
Prof Laura Green	University of Birmingham
	FSA Science Council
Mr Steve Wearne	FSA, Director of Science
Ms Julie Pierce	FSA, Director of Openness, Data and Digital
Mr Leigh Sharpington	FSA, Regulating our Future Manager
Mr Martin Evans	FSA, Head of Field Operations
Ms Alice Biggins	FSA, Head of Regulatory & International Unit
Mr David Lau	FSA, Strategic Evidence Delivery Lead
Dr Anusha Panjwani	FSA, Science Partnerships and Communications Lead
Dr Patrick Miller	FSA, Head of Scientific Strategy and Governance
Dr David Self	FSA, Head of FSA Private Office
Jesus Alvarez-Pinera	FSA, Head of Scientific Methods and Laboratory Policy
Ms Heather Ruscoe	PhD placement
Dr Ben Goodall	FSA, Private Secretary to Chief Scientific Adviser
Mr Caspar Donnison	Government Office for Science
Ms Ruth Edge	National Farmers' Union
Ms Michelle Patel	FSA, Head of Social Science Transformation
Mr Derek Flynn	Consultant