TEAGASC TECHNOLOGY FORESIGHT

FUTURE TECHNOLOGIES FOR A COMPETITIVE AND SUSTAINABLE IRISH AGRI-FOOD INDUSTRY

TECHNOLOGIES SCOPING DOCUMENT

Agriculture and Food Development Authority

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1. Introduction

1.1 Teagasc is undertaking a Technology Foresight exercise as a follow- up to *Teagasc 2030*, the Foresight project completed in 2008. (http://www.teagasc.ie/publications/view_publication.aspx?PublicationID=285). The new project will focus specifically on the identification of the key technologies that have the potential over the next 20 years or so to underpin competitiveness, sustainability and growth in the Irish agri-food and bioeconomy sector.

1.2 The overall objective is to provide a comprehensive and well-researched source of evidence for policy decisions relating to Teagasc's future science and technology programmes. It will aim to assist Teagasc in identifying the new areas of technology which it should prioritise for the long-term and the resulting implications for investment in new skills, equipment and infrastructure. It will also to bring together a wide diversity of people from different backgrounds to explore new ideas and to achieve consensus on the long-term challenges confronting the Irish agri-food and bioeconomy sector and its future technology needs.

1.3 The focus of the exercise is on the Irish agri-food and bioeconomy sector and, in particular, on its future technology needs. The primary user of the project outputs will be the Teagasc Board and management, assisting them in defining a long-term research agenda, as well as identifying future staffing, skills, and other organisational resource needs. The results will also feed into wider sectoral policy making and possibly influence other actors in the S&T arena.

1.4 Agriculture and food constitute a hugely significant element of the Irish economy in terms of jobs and exports, and its long-term competitiveness and sustainability is a priority concern of national policy. The continuous development and application of new knowledge and new technologies is crucial to the realisation of national policy objectives for the sector. As the national organisation with responsibility for the development and dissemination of the sector's technology needs, Teagasc has a responsibility to invest in developing not just short-term solutions or technologies to address the challenges of the next five years or so, but also to make strategic investments in ground-breaking research that has the potential to enhance the performance of Irish agriculture and food in the longer term. Foresight is the process by which this fundamental task can be successfully undertaken.

1.5 In preparation for the Foresight launch, this scoping document aims to identify and provide an assessment of the emerging technologies that could impact on the Irish agri-food and bioeconomy sector up to 2030 and beyond, focusing on those likely to yield the greatest economic, environmental and social benefits. The document will, in the first instance, be presented to the Steering Committee being established to guide the Foresight project and will subsequently form a key input in the work of the

Technology Cluster Working Groups, which will be established to conduct the actual Foresight analysis.

1.6 This document is not intended to be an in-depth review of all new and emerging technologies that could at some stage impact on Irish food production/processing, but rather is an initial high-level input to the Foresight process. This process will, over a twelve-month period, draw on the expertise of a wide range of national and international experts and industry stakeholders to assess in greater detail the potential relevance of these technologies to Teagasc and to the future growth, competitiveness and sustainability of the Irish agri-food sector. The experts will also conduct an in-depth analysis of the barriers to the uptake of the technologies and the likely costs and timescales involved.

2. Context: The Irish Agri-Food Sector and Bioeconomy

National Strategy for a Global Market

2.1 Under ***Food Harvest 2020*** (http://www.agriculture.gov.ie/agri-foodindustry/foodharvest2020), the current national strategy for the sector, agri-food remains Ireland's largest indigenous industry, continues to play an essential role in the country's economic recovery, contributing €26 billion in turnover and generating 12.3% of merchandise exports. The sector accounts for around 170,000 jobs or 9% of total employment, and makes a particularly important contribution to employment in rural areas. Food and beverage exports increased to a record value of almost €10.5 billion in 2014, representing an increase of 4% on the previous year and a 45% increase since 2009.

2.2 A committee of leading figures from the agri-food sector, appointed by the Minister for Agriculture, Food and the Marine, is preparing a new national strategy for the sector covering the period up to 2025. The new strategy is expected to address actions designed to maximise the sector's potential for sustainable growth and job creation; enhance farm and firm-level productivity and efficiency; increase farm incomes; and maintain and increase the sector's capacity to secure European and global trading opportunities. It will also seek to build a basic level of resilience against changing environmental conditions, price fluctuations and financial uncertainty.

2.3 The Committee is also expected to identify strategies to help Irish producers and processors move up the value chain and diversify the product mix as a means of enhancing overall sectoral value and protecting it from volatile commodity prices. Policy will be expected to continue to facilitate and support product diversification through further investment in product innovation and in new process technologies.

2.4 The new strategy is expected to benefit from the opportunities arising from growing global food demand. United Nations studies project global population to grow to 9.1 billion in 2040 and to around 10 billion in 2050. Assuming current patterns of food consumption persist, the resulting aggregate increase in food demand is projected to be in the region of 60% on 2007 levels (FAO, 2011 and 2012). This larger population will also enjoy much higher incomes. The US Grains Council (2011) forecast that real purchasing power parity *per capita* GDP measured in USD will more than double from $9,727 in 2010 to $24,697 by 2040. Rising prosperity, combined with continuing population growth, means consumers will consume more meat, dairy, vegetable oils, fruits and vegetables, fish, and sugars in average diets worldwide.

2.5 In responding to these growing market opportunities, Ireland can benefit from the technology revolution currently underway. Breakthroughs in nutrition, genetics, informatics, remote sensing, precision farming and low impact agriculture, among others, can further improve livestock and crop yields while reducing their environmental impact.

Sustainable Intensification in Farming

2.6 Policy makers and scientists agree that the world cannot adopt a "business-as-usual" approach in producing the additional food needed by a growing and more wealthy world population. Producers will need to modify their methods in a way that will not further degrade the environment nor further compromise the world's capacity to produce food in the future. It will also be critical to tackle waste and consumption distribution. These challenges are as relevant to Ireland as elsewhere-and possibly even more so, given the country's positioning in the marketplace as a producer of premium quality, "clean, green" food.

2.7 This means that Ireland will have to focus on options for increasing farm-level productivity and efficiency and ensuring environmental sustainability through greater resource efficiency. Increasing the emphasis on resource efficiency so that more can be produced over time with fewer inputs will contribute to both productivity and sustainability, help increase the viability of agriculture and reduce Ireland's global environmental footprint.

2.8 The term "sustainable intensification" is often used in referring to the production of more food from a fixed or slightly declining land area, while reducing environmental impacts and respecting social and economic priorities. A core principle of sustainable intensification is that it is dependent on the ***greater application of knowledge per hectare***. Accordingly, the intensification of Irish agriculture will not be mainly concerned with the use of more fertilisers, pesticides or machinery applied per hectare, but with the practice of much more knowledge intensive management of scarce resources to produce food and environmental outputs with minimal disturbance to the natural environment (RISE Foundation, 2014).

2.9 However, the term has come in for criticism in recent times and we do need to consider it in specific geographical and policy contexts. The RISE Foundation (2014) argues that the role of European sustainable intensification must be to demonstrate how high intensity, productive agriculture, can be combined with much higher standards of environmental performance. "The emphasis has to be to find ways to continue the process of technical change in food production to radically improve the resource efficiency of European agriculture and in the process to meet European citizens' ambitions for high standards of biodiversity, climate, soil, water and cultural landscape protection. In short, in the EU, interpretation of sustainable intensification must place most emphasis on improving sustainability" (p.76).

2.10 In the developing world, where the goal of food security is the overriding one, Loos *et al.* (2014) argue that sustainable intensification is likely to be unsuccessful in delivering on food security given its narrow focus on food production to the detriment of other actions needed. Godfray and Garnett (2014) also agree that SI needs to be integrated within a much broader range of actions in order to deliver on food security and broader food system sustainability.

2.11 Multiple approaches will be required in implementing sustainable intensification, including the adaptation of existing farming techniques, the development of completely new production systems and the creation of novel approaches to crop and livestock genetic improvement. Underlying all of these new approaches will be a requirement for greater effectiveness in anticipating new challenges and in modelling potential solutions based on a greatly enhanced data analytical capacity.

2.12 There are two fundamental pathways by which sustainable productivity growth in farming can be achieved: (i) by developing, adapting and applying new technologies and practices for agricultural production and farm management; and (ii) by increasing and accelerating the more widespread adoption and application of existing technologies and practices. The first pathway enhances the potential for more productive use of resources by expanding the frontier of production possibilities. The second enables farmers to gain more of this potential growth by advancing towards the existing production possibilities frontier, i.e. closing the yield gap. The principal focus of this paper is on the first of the two pathways, i.e. on how new technologies and practices can support Irish agriculture to achieve greater productivity while meeting the many current and future environmental and other challenges.

2.13 Of course, the take-up and adoption of technologies by farmers is essential. We can generate new technologies, but if adoption rates continue to be very low then there will be no positive impact from the technology. Accordingly, support for efficient and effective farmer education and training and extension services will continue to be necessary.

Sustainable Food Processing

2.14 The development of new products and new technologies is essential for most food processing companies to remain competitive and to grow. Failure to do so places companies in the "commodity spiral", where price is the main (and sometimes the only) basis of competition.

2.15 For Irish food companies in general, just as with their EU counterparts, new product development is dominated by incremental change (*me-too* products, alternative flavourings, etc.); a relatively small part is related to technological innovations (STOA, 2013).

2.16 Nevertheless, demographic changes as well as sustainability concerns, offer plenty of opportunities for more innovation in the food sector. The markets in the US, EU and Japan account for over 60% of total retailed processed food sales in the world (Winger and Wall, 2006). Added value products are the main source of growth in these markets (STOA, 2013).

2.17 ***Food Harvest 2020*** set targets for increasing the production of value-added food products based on increased growth in the volume of primary output. The Strategy set a vision for Ireland's food industry as a leading exporter of quality food products, characterised by growing sales to an increasingly diverse range of markets, and with a greater proportion of exports accounted for by high value-added products.

2.18 The food industry in Ireland currently devotes approx. 0.65% of turnover to business expenditure in research and development (BERD). Scope exists to increase this low level of investment to bring it more in line with that of the industry in major competing nations. ***Food Harvest 2020***, referencing international benchmarks, calls for a doubling of the BERD to 1.3%. To achieve this, a new and targeted approach to innovation is required built on the application of new technologies.

The Irish Bioeconomy

2.19 The EU Bioeconomy Strategy (European Commission, 2012) defines the bioeconomy as an economy which encompasses the sustainable production of renewable biological resources and their conversion into feed, food, bio-based products such as bio-plastics, bio-fuels and bio-energy. It includes agriculture, fisheries, forestry, food, pulp and paper and chemical, biotechnology (incl. pharmaceutical) and energy industries.

2.20 The European bio-economy employs some 21.5 million people and represents an annual market worth over €2 trillion, with significant potential for further growth, as EU member states supplement food production with sustainable technologies for production of biofuels, bio-fertilisers, bio-chemicals and bio-plastics. The EU is rapidly moving to replace the petro-chemical technologies with new, sustainable bio-technologies that utilise renewable resources. This development is designed to mitigate the resultant environmental issues as well as social issues that will arise as finite supplies of mineral resources are depleted. Development of these new technologies opens up new, lucrative markets that are only just beginning to be exploited.

2.21 Ireland has many natural resources that can be leveraged to sustainably produce new forms of bio-products and engineer new process technologies. However, it is only beginning to use these resources to tap new bio-economic opportunities. The economic value of Ireland's current bio-products are at the lower end of the value spectrum (e.g. commodity food products and bio-energy) and development of much more lucrative bio-chemicals or bio-materials outputs has not yet been prioritised. Other potential opportunities may be underexploited (e.g. the marine sector) or overlooked altogether (e.g. resource recovery and redeployment).

Sustainable Food Systems Approach

2.22 In approaching this project, Teagasc has the capacity to view agriculture and food from a total systems perspective encompassing the production, processing, transport and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes (http://www.futureoffood.ox.ac.uk/what-food-system).

3. Generic Technologies: Considering the Options

3.1 Historically, agricultural productivity growth has enabled significant increases in food production, far exceeding growth in population and leading to a long-term downward trend in real food prices. Over the last half century, global agricultural production increased more than three-fold, while the world's population expanded by 126 per cent. Global cereal production grew by almost 200 per cent, although the area harvested increased by only 8 per cent (FAO, 2014).

3.2 This remarkable growth in production has, however, been associated in many parts of the world with adverse environmental consequences. Future growth must not only involve improved productivity, but also superior resource efficiency and enhanced environmental performance. These challenges will require the deployment of new technologies, processes and knowledge underpinned by good science and consumer acceptance.

3.3 Some of the technologies considered in the following sections build on existing knowledge and applications in agri-food (***incremental innovation***), while others are completely radical (***disruptive innovation***) and will require a great deal of further research before they can be even considered for application in food production or processing, and even then, barriers such as regulation, cost and consumer resistance may further impede, or even totally prevent, their take up by the sector.

Disruptive Innovation

3.4 The world is experiencing a spate of disruptive innovation from rapidly accelerating scientific discoveries and new technologies. These are causing fundamental shifts in our economic landscape and introducing new risks and opportunities for the economy, the environment and society. Advances in big data, 3D printing, artificial intelligence, robotics, nanotechnology and biotechnology are already altering existing economic systems and business models. Each of these core technologies is also reinforcing and expediting the development of the others, leading to an even faster pace of change (Policy Horizons Canada, 2012).

3.5 It is conceivable that such technologies could ultimately impact almost every sector of the economy. One of the most disruptive features of several of the technologies is the manner in which they can boost productivity with fewer workers. Artificial intelligence along with data analytics could fundamentally change the service sector, resulting in far fewer job opportunities. The economics and location of manufacturing in a growing number of sectors could be changed by 3D printing, while synthetic biology could utterly change the economics and flow of raw materials in agriculture, forestry, energy and mining, amongst many other economic sectors.

3.6 Ireland cannot disregard nor minimize the potential rate and extent of change resulting from these technologies, including in agri-food. To do so, could very well threaten our future competitiveness, preparedness and resilience. Instead, in agri-food, we must be clear as a nation as to what our vision is for the sector; how some or all of the many new technologies discussed in the following pages could help achieve that vision and what policies and strategies will support the use of those technologies.

Technology Pull

3.7 This project recognises that innovation is driven by consumer demand flowing from retailers and processors through complex and varied modern food and farming supply chains. Industry and the research base need strong partnerships to pull technologies and innovations from the laboratory to the farm and through the supply chain. Ultimately it is consumers who will determine the success or failure of new technologies. Consumers are increasingly interested in food provenance, traceability and safety. Increasingly, their food choices are determined by clear information, trust and acceptability of products, production methods and technologies.

New Technologies Overview

3.8 **Biotechnology** has, for a number of decades, made an important contribution to agri-food, and it continues to produce new tools and techniques based on molecular and genomic approaches to food, nutrition, health and wellbeing. Biotechnology offers the potential for greater production and processing efficiency, as well as new benefits for consumers. It may permit better and more efficient use of raw materials and by-products through improved and novel enzymes and microbes optimised for fermentation. It could also help guarantee food safety and ensure traceability across the food chain, as well as leading to the development of more specific and improved vaccines and therapies to enhance animal health and generate the next generation of health-promoting (probiotic) microorganisms (Government Office for Science, 2012). Biotechnology could also assist in reducing or eliminating waste at all stages of food production, processing, distribution and storage.

3.9 A number of **genetically modified biotechnologies** are ‘in the pipeline’ and ready to support development of crop varieties over the next decade; however, significant ethical and regulatory barriers still exist in Ireland and many other countries to the adoption of genetically modified crop varieties (Government Office for Science, 2012).

3.10 Addressing Ireland’s **CO_2 emissions and other environmental challenges** will require new approaches, which could involve use of engineered feed stocks to reduce CO_2 emissions from livestock; conversion of CO_2 to methane fuel; use of bio waste to synthesise biogas and syngas though anaerobic digestion; use of algae to mop up CO_2 and ameliorate water quality; development of long-life food to allow low-carbon transport; and recycling of waste to produce non-petroleum-based fertilizers (Government Office for Science, 2012).

3.11 New and improved **agri technologies**, including precision farming and vertical farming, are lessening our reliance on traditional farming methods. Precision farming allows farmers to increase the efficiency of their operations and to develop new farming practices. Vertically integrated agriculture, in which large-scale agriculture occurs in high-rise structures, minimises land requirements for food production.

3.12 Recent research has highlighted the potential for **nanotechnologies'** use in a wide range of agriculture and food applications, including new supplements, novel food packaging, increased range of food textures, colours and tastes, and targeted crop pesticides. As a result, it is likely that radical changes will emerge in the way food is perceived, stored, packaged, transported, monitored, consumed and processed (Cushen *et al.*, 2012).

3.13 There are new opportunities emerging for the rural sector to improve its level of productivity and develop new markets. These opportunities are being created by the rollout of a next generation network broadband and through the growing impact of the **digital economy**. The rollout of broadband and sensor networks (the "internet of things"), accompanied by new information services, could not only transform the practice of agricultural industries but also the relationships with upstream service, food processing, logistics and retail industries (CSIRO, 2013).

3.14 It is recognised that the opportunities and risks associated with these and other new technologies, and their associated management, need to be considered on a case-by-case basis and assessed against the specific problem or issue the technologies can address. It will be important to look to developments in the **social and economic sciences** in conducting these assessments, as, amongst other socio-economic considerations, consumer attitudes will be critical in determining the ultimate application of these technologies in agri-food. Moreover, the development of **new farming systems** (through computer modelling and actual systems on the ground) will be crucial in the extension process to farmers, as will farmers' and processors' willingness and ability to embrace technologies.

3.15 A further major consideration in the context of the Foresight project, and in the subsequent development of a new Teagasc Research Programme, is that many of the technologies considered in this document owe their current state of development and commercial impact overwhelmingly to investment by the private sector. In some instances, public sector research involvement is miniscule. Accordingly, in the course of the Foresight exercise, questions will have to be addressed regarding the proper role (if any) of public sector research in the future development of these technologies, particularly in a small economy such as that of Ireland.

4. Biotechnology

> **Over the next 40 years, biological science-based technologies and approaches have the potential to improve food crop production in a sustainable way. Some of these technologies build on existing knowledge and technologies, while others are completely radical approaches which will require a great deal of further research.**
>
> **The Royal Society, 2009**

4.1 Biotechnology is here defined as "any technological application that uses biological systems, living organisms or derivatives thereof, to make or modify products or processes for specific use." (UN Convention on Biological Diversity, Art. 2). It encompasses a myriad of procedures for modifying living organisms and has been employed in agriculture in various forms from earliest times. Modern biotechnology draws on a range of different technologies, including genetic engineering, cell and tissue culture, as well as knowledge and methods from outside the field of biology, particularly from the field of Bioinformatics.

4.2 To date, agriculture has benefited in two principal ways from the application of biotechnology: firstly, by increasing the rate of gain and extending the range of traits that can be included in plant and animal breeding programmes; and secondly, by providing molecular insights and tools that can be used to improve plant and animal management, based on understanding of the interactions between management and genomes (Teagasc, 2009).

4.3 In food processing, biotechnology makes use of microbial inoculants to enhance properties such as the taste, aroma, shelf-life, texture and nutritional value of foods through fermentation, which is also widely applied to produce microbial cultures, enzymes, flavours, fragrances, food additives and a range of other high value-added products (FAO, 2010).

4.4 Arising from the rapid expansion of molecular biology, potential applications in agriculture have widened allowing us to understand and alter animal and crop production in new directions and at a much increased rate. Recent advances also provide scope for better protection of the environment and enhanced competitiveness of the food processing sector.

4.5 Techniques of modern biology such as molecular cloning of genes, gene transfer, genetic manipulation of animals and plants, embryo transfer, genetic manipulation of rumen microbes, genetically engineered immunodiagnostic and immunoprophylactic agents as well as veterinary vaccines (specifically **marker** vaccines), *inter alia*, are a reality today and are finding their way into research and development programmes around the world (Government Office for Science, 2010).

4.6 Advances with next-generation sequencing of nucleic acids and mass spectrometry-based analysis of proteins and metabolites are leading to rapid gains in throughput and dramatic reductions in cost. Current methods using these technologies are most useful for obtaining additional sequences from species for which whole-genome data are already available. The technologies have already advanced to the point that it is 'cheap and routine' to sequence the genomes of microbes and it will not be long before this will also be possible for larger genomes. After that point, the movement will be toward understanding how these genes are expressed and controlled (by food and other factors), i.e. transcriptomics rather than genomics. Massive potential exists to exploit the wealth of high-throughput data through bioinformatics and to incorporate the information into accelerated breeding and improved management of plants and animals (Government Office for Science, 2010).

4.7 In the area of animal health, for example, until the advent of DNA sequencing-based methods to identify bacteria (and viruses), culture-based methods could only identify a fraction (~3%) of microbes present. DNA-based sequencing can now identify everything that is there. This will revolutionise our understanding of disease. Host-pathogen interactions have been evaluated in a very simplistic way previously and more comprehensive knowledge will enable new breakthroughs in diagnosis and treatments.

Plant Biotechnology

4.8 Plant biotechnology employs the latest methods of molecular biology, including genomics, proteomics, metabolomics, and systems biology. Ideally, it aims to generate plants (ideotypes) that are designed for specific agricultural, horticultural, medical, and industrial purposes (Kirakosyan and Kaufman, 2009). The rapid developments in this field have revolutionized our concepts of sustainable food production, cost-effective alternative energy strategies, environmental bioremediation, and production of plant-derived medicines through plant cell biotechnology.

4.9 However, many challenges in translational and applied plant biology remain to be addressed; specifically in regards to the 'trade-off' that could be associated with the introduction of novel varieties and associated management systems versus existing regimes On the one hand, there is a need to improve existing plant characteristics for better crop performance, particularly with respect to improving yield and stress tolerance in crops to enable them to adapt to changing environments. On the other, there are many new functions and tasks that we might envision for plants, such as biosensing and producing valuable compounds (Ananda Kumar, 20). In essence, the implementation of biotechnology-derived/supported systems requires a refocusing of the 'traditional' view of tillage and horticultural production in light of the environmental and legislative challenges Ireland will face into the future.

4.10 There are two main routes by which biotechnology can be used to positively influence the genetic improvement of food, feed, ornamental and industrial feedstock crops. The first route involves the engineering of crop genomes via transgenics, cisgenics or intragenics. While the traditional view of GM relates to transgenesis, the recent development of cisgenics is, to all intents and purposes, a way to merely accelerate breeding between two compatible species that otherwise would require multiple stages of back-crossing to deliver an agronomically superior variety.

4.11 The development of genome editing is a ‘next generation’ technology that comprises a whole suite of novel, highly targeted approaches (e.g. zinc finger nucleases, TALENs, CRISPR/Cas9) based around hybrid proteins which can recognise specific DNA motifs and subsequently delete/replace nucleotides in a plant genome. By acting as a ‘molecular scissors’, the ability to edit an existing genome without the need to add novel DNA sequence (via transgenic/cisgenics/intragenics) is revolutionary both in its ability to deliver germplasm with novel phenotypes but also in how it is being perceived by regulatory agencies, who recommend it be excluded from current GM regulatory processes.

4.12 The second application involves the use of genotyping approaches in conventional breeding programmes with the goal of making selection more efficient and reducing the time per cycle of selection. The older iteration of this technology, Marker Assisted Selection (MAS), has been much more useful in plant genetic improvement than in animal genetics due to a larger number of useful single gene targets in the former (e.g. disease resistance genes). Many significant advances have been achieved in plant breeding with MAS, but it has consistently failed to offer significant improvement in complex polygenic traits such as yield. The advent of massively parallel genotyping technologies opens the prospect of applying genome-wide selection (GS) approaches. Unlike MAS, which fit quite well into existing breeding schemes, truly efficient GS in plant breeding might involve a radical redesign of breeding systems for many species. It’s worth noting that a major potential bottleneck in augmented plant breeding approaches is likely to revolve around the ability (or lack thereof) to phenotype large populations effectively, especially at a field level, below ground, and for compositional characteristics. Phenotyping will be a key pillar of successful augmented plant breeding in the future.

4.13 As the availability of effective pesticide chemistries decreases due to the dual pressures of regulatory constraints and the constant emergence of fungicide resistance, there is an increased need to develop integrated pest control measures. Biotechnology has a crucial role to play in this integrated approach. Through the use of targeted next generation sequencing and extensive sampling networks (spore traps, bait plants, field samples, etc), signature changes in a pathogen’s genome related to fungicide resistance or virulence on a plant host virulence can be detected at the level of single spores. Developing detection systems that inform farmers about not only what disease is prevalent in the environment, but also to know whether the samples strains are resistant/tolerant to specific chemistries and or deployed resistance genes, presents a unique opportunity to generate ‘smart’ disease control strategies that have the potential to reduce production costs and decrease the chemical load applied to the environment.

Box 1. Drivers of Biotechnology Adoption in Agri-Food

Responding to global and regional priorities, including challenges of climate change and legislative directives, increasing demand for food due to population increases and stagnation of yield improvement in cereal crops, changing consumption patterns, and increasing concerns over energy and human health.

. ***New approaches for crop genetic*** improvement based on massively parallel genotyping technologies that are expected to radically increase the efficiency of conventional breeding, Although "big-players" will be early adopters of this technology, unlike the (possibly changing!) GM/GE situation, there are fewer barriers to participation.

The development of novel genetic engineering approaches such as cisgenics and targeted genome editing provides opportunity to address policy impediments while delivering novel varieties of agronomic importance.

GE/GM approaches are moving beyond the traditional focus on herbicide and insect resistance into drought and cold resistance, stacking multiple traits and improved output traits for food or industrial products.

The rapid development of the market for biofuels and bioproducts – The bioengineering and bioprocessing industry is quickly becoming a major market for agricultural biomass and the level of integration between industrial and agricultural biotechnology will continue to increase dramatically. A bio-refinery approach to agricultural value will permit the capture of all the different potential value streams from agricultural and horticultural products.

Sparling ***et al.(2010)***

4.14 Investment in structural and functional genomics of plant species will virtually revolutionise the complexion of agricultural biotechnology as well as human health care (Liu *et al.*, 2013). With the full understanding of plant genome structure, a host of useful genes will be available as targets for manipulation via GM, genome editing or augmented conventional breeding approaches. Harnessing genome information could also result in significant developments in conventional breeding. For instance, it is noteworthy that the most rapid increases in yield for many crops have coincided with the introduction of hybrid breeding. This change has yet to be applied to many species. Combining genomic information, wide crosses, natural mutants (and possibly GE/GM) to re-engineer the reproductive biology of crops has the potential to address stagnant yields in species where hybrid seed technology doesn't exist.

4.15 The development of systems biology has facilitated the modelling of biological systems and processes and provided a systems-level view of these processes. Advances in genome-wide analyses and computational studies will permit a better understanding of complex regulatory and metabolic pathways. As such, the next iteration of technological advancement will depend on how we use systems biology for the discovery and better understanding of genes and pathways that can be modified using the new genetic tools (Liu *et al.*, 2013). In addition to understanding pathways, understanding plants as communities will become an important idea in systems biology. In many agro-ecosystems (e.g. grasslands), plants exist as communities of diverse genotypes and species which are experiencing interactions and selective forces throughout the growing season (e.g. grazed swards in pastoral production systems). Understanding the interactions of such communities at, for example, a genomic level, will enhance our ability to design superior varieties for end users.

4.16 In addition, the enormous potential offered by synthetic biology in future plant science and applications is close to being realised. Synthetic biology strives to replace or reconfigure genetic components that are found in nature using synthetic tools.

Animal Biotechnology

4.17 There is general agreement that increases in the demand for livestock products will continue beyond 2040, mainly driven by human population growth, income growth and urbanization (Thornton, 2010). However, it is possible that in developed countries, in particular, which already experience high consumption levels of meat and dairy products, future demand could be seriously moderated by socio-economic factors such as concerns regarding human health, animal welfare and changing socio-cultural values (….).

4.18 Given the dependence of the Irish agricultural sector on livestock production, this scenario opens up major opportunities for Irish farmers and processors, but also raises fundamental challenges which will demand the on going application of the best technology to ensure far greater efficiencies in our future production systems.

4.19 Increases in past livestock productivity have, in the main, been driven by the application of animal science and technology, and new developments in breeding, nutrition and animal health science and technology will be needed in order to further enhance production, efficiency and genetic gains (Thornton, 2010).

4.20 Breeding strategies to improve efficiency of livestock production comprise selection schemes amongst populations, crossbreeding and biotechnological techniques to enhance the productive and reproductive performance or combination of such strategies. Selective breeding has been very successful at increasing productivity-through selection for high milk yields or growth rates, for instance-but there has been limited selection of those traits related to product quality. Genomics offers the opportunity to identify markers associated with quality features (meat tenderness or juiciness, milk composition, etc.) for use in marker-assisted selection.

4.21 Thornton (2010) states that future livestock breeding will focus on attributes such as product quality, enhanced animal welfare, disease resistance and the reduction of environmental impact. Molecular genetics tools will play a key role. Transgenic livestock for food production may feature in future along with new dissemination methods such as cloning. The existence of complete genome maps for some species presents opportunities for possible advances in evolutionary biology and animal breeding, paving the way for possible dramatic changes in livestock production.

4.22 Genomic selection should be able to greatly increase the rate of genetic gain in livestock, as it enables selection decisions to be based on genomic breeding values, which can ultimately be calculated from genetic marker information alone, rather than from pedigree and phenotypic information. Genomic selection is not without its challenges, but is revolutionizing animal breeding schemes.

4.23 Teagasc, working with the Irish Cattle Breeding Federation, has been at the forefront of applying more advanced genotyping tools resulting in an increased rate of genetic gain through the use of genomic selection of bulls and cows for milk production traits (Teagasc, 2009).

4.24 In parallel, reproductive technologies (ovulation induction and control to improve reproductive/management of farm animal reproduction will also be important, particularly as herd size increases and labour input per cow declines) will continue to advance to allow acceleration of genetic selection, probably including recombination in vitro. Transgenesis and/or mutagenesis will be applied to introduce new genetic variation or desired phenotypes (Hume, Whitelaw and Archibald, 2011).

4.25 In the area of animal nutrition, advances in genomics, transcriptomics, proteomics and metabolomics will be important and in predicting animal growth and development. Better understanding of the processes of animal nutrition could also contribute to improved management in the area of reproductive performance and in the mitigation of greenhouse gas emissions.

4.26 While recent decades have witnessed a general reduction in the burden of livestock diseases as a result of more effective drugs and vaccines and progress in diagnostic technologies and services, new diseases of concern have emerged (e.g. avian influenza H5N1) and, in the longer term, there has to be concern regarding disease trends being heavily modified by climate change.

4.27 The spread of new diseases resulting from climate change is a critical challenge facing animal production in the years ahead. Comparative genomics and genetics will provide insights into the molecular basis of disease susceptibility that will permit rational selection. Combinations of transgenesis and selective breeding will reduce these impacts. Major endemic diseases, as well as new diseases, may be mitigated by selection of resistant animals or by genetic modification and maximizing the welfare of animals. Continued selection can also improve feed conversion and any other trait of interest. Selection will be applied to animals to optimize their adaptation to particular feeds or environments. Mutation and selection for animals that have substantially reduced methane production by virtue of both further improvements in food efficiency and altered rumen environment are therefore possible future paths (Thornton, 2010).

4.29 To control disease within animal populations, particularly zoonotic disease, a focus on the **source** is likely to be much more effective than waiting for emergence in the food chain or in human populations. There is huge potential to study transmission dynamics of bacteria and viruses on farm/production units with a view to reducing the opportunity for spread.

4.30 In the area of animal management, functional genomics is providing new insights into the responses of individual animals – for example in relation to immune responses (pathogens, vaccines) or stress responses (climate, housing). A lack of understanding of the regulation of the immune response, for example, contributes to the lack of efficacy of new vaccines. Understanding the factors contributing to inter-animal variation in immunity will be critical to overcoming future disease challenges. New insights into the interaction between environmental factors, such as diet, pathogens and climate, and genomes will help us to develop novel management strategies. It is envisaged that these could be delivered at the level of groups of animals or individuals. For example, it will be important to understand genotype × environment interactions to refine management regimens for animals, whilst it is also possible to envisage 'personalised' managements based on individual genotypes. These management strategies will deliver improvements against the wider range of consumer expectations, including product quality, animal welfare, and environmental effects of ruminant production systems (Teagasc, 2009).

4.31 The development of genetic and biochemical markers will have applications for monitoring and managing animals. For example, transcriptome profiling and identification of novel biomarkers in blood will increasingly be used for a range of clinical purposes, including disease classification or diagnosis, prognosis, as well as treatment, monitoring and surveillance. The translation of genomic biomarkers to clinical practice will depend on several factors, including the accuracy of testing methodologies, and the strength of correlations with clinical phenotype or stability of the biomarker and the ease with which the biomarker can be measured.

4.32 There are a range of other applications of animal biotechnology that would involve the development of new industries. These include 'Biopharming' – the production of human pharmaceutical proteins, such as clotting factors, in animals; and 'Xenotransplantation' – the production of organs for transplant from animals into humans (Teagasc, 2009).

4.33 Metagenomics is an emerging field of molecular biology that uses high-throughput sequencers to identify genes in complex microbial systems. The rumen microbiome is well adapted to exploit fibrous forages. However, small populations of micro-organisms have a range of negative effects, including production of the potent greenhouse gas methane (methanogenic Archaea), production of ammonia (Hyper-ammonia producing bacteria) and hydrogenation of polyunsaturated fatty acids, making ruminant fat highly saturated. By providing a complete description of the rumen microbiome, metagenomics will allow us to probe the basis for the persistence of these micro-organisms in relation to interactions between micro-organisms and diet manipulations, as well as animal factors affecting the rumen environment (Teagasc, 2009).

4.34 Likewise in monogastric animals, the profile of the microbiome of the gastrointestinal tract changes with age (in pigs) and can be altered by diet and environental conditions. A greater understanding of the gut microbiome will lead to strategies and interventions for improved intestinal health and production performance. The interplay between the monogastric microbiome, intestinal function and diet needs to be fully understood for this to happen.

4.35 Arguably, the single most important application of Biotechnology in the coming years is to develop new classes of antimicrobials. Animals could have a critical role to play here, as they have diverse repertoires of antimicrobial peptides (for example) that do not exist in other species and because they have not co-evolved with (some/most) human pathogens could have useful efficacy, e.g. against Campylobacter. Bovine peptides are being used in diabetic foot creams as well as adjuvants for vaccines.

Food Biotechnology

4.36 Many points raised in relation to animal biotechnology are relevant in food processing. Functional genomics is relevant to food biotechnology, e.g. responses of humans (or subsets of humans) to specific foods in terms of, for example, probiotics and impact on health. Functional genomics of microbes (probiotics, starter cultures and other microbes of technological relevance) will also be important.

4.37 (FAO) Biotechnology in the food processing sector uses micro-organisms for the preservation of food and for the production of a range of value-added products such as enzymes, flavour compounds, vitamins, microbial cultures and food ingredients. Applications target the selection and manipulation of micro-organisms with the objective of improving process control, product quality, safety, consistency and yield, while increasing process efficiency.

4.38 Biotechnological processes applicable to the improvement of microbial cultures for use in food processing applications include traditional methods of genetic improvement (“traditional biotechnology”) such as classical mutagenesis and conjugation. These methods generally focus on improving the quality of micro-organisms and the yields of metabolites. Hybridization is also used for the improvement of yeasts involved in baking, brewing and in beverage production.

4.39 Recombinant gene technology is widely employed in R&D for strain improvement. The availability of genetic manipulation tools and the opportunities that exist to improve the microbial cultures associated with food fermentations are tempered by concerns over regulatory issues and consumer perceptions. GM microbial cultures are, however, used in the production of enzymes and various food processing ingredients such as monosodium glutamate, polyunsaturated fatty acids and amino acids.

4.40 Biotechnology, including genetic engineering technology, is playing an important role in the production for functional foods. Functional foods, also known as Nutraceuticals, are likely to play a greater role in the area of preventive medicines and might help tackle health-related issues.

4.41 Lactic acid bacteria and probiotic microorganisms in fermented foods have been used for many years for health reasons and are now an attractive alternative in the treatment of intestinal disorders, and appear to impact the immune system via stimulating protective immune cells. Through genetic engineering, it is possible to strengthen the effect of existing probiotic strains and create completely new probiotics with multiple health benefits These natural or genetically engineered beneficial bacteria might alter the ratio of “good to bad bacteria “that inhabit the intestine and might specifically block activity of food borne pathogens to prevent gastrointestinal diseases.

4.42 Biotechnology is also widely employed as a tool in diagnostics to monitor food safety, prevent and diagnose food-borne illnesses and verify the origins of foods. Techniques applied in the assurance of food safety focus on the detection and monitoring of hazards whether biological, chemical or physical.

4.43 There is a growing demand among consumers for "natural foods" with "clean labels” that have less additives (E-numbers) and preservatives. Leading European retailers have already produced lists of additives that they do not wish suppliers to use in an attempt to meet consumers’ expectations and increase products’ appeal. This desire for a “clean label” is posing many challenges for food manufacturers, as the removal of traditional anti-microbial preservation methods and chemical preservatives, may allow enhanced survival of food- borne pathogens and a higher risk of serious food-borne outbreaks. In parallel, insufficient shelf-life contributes to economic losses for the food industry and to food waste from spoilage. Thus, there is a need for biotechnology to deliver natural agents which are “clean label, but which give the required anti-microbial activity whilst maintaining the sensory qualities of the food demanded by the consumer.

4.44 Whole genome sequencing and metagenomics have significant potential to be applied as tools to identify sources and types of contamination in food production systems. Metagenomics, for compositional analysis of the microbiota in high risk sites of contamination in the factory environment (equipment, surfaces etc) could support studies on the persistence, ecology and control of pathogens and key spoilage micro-organisms at such sites. Metagenomic analysis on food samples as they progress through production, processing and storage will yield key information between pathogens and how the microbiota changes as result of environmental factors (pH, temperature etc.) would support studies on prediction of shelf-life.

4.45 There is huge potential for biotechnology to deliver alternative biocontrol approaches (vaccines, bacteriophage, competitive exclusion, etc.) for *in vivo* control of pathogens of relevance to animal health, and food safety. Advances in this area would also reduce usage of antibiotics in food animal production and help address the ever-growing problem of anti–microbial resistance to a range of human clinically relevant drugs.

4.46 Technologies for reducing and recycling of food waste for added value will gain increasing importance in the coming decade. This will require a two-pronged approach: 1) technologies which reduce food spoilage, extend shelf-life in line with consumer requirements, as well as technologies which allow retailers to better predict shelf-life and better manage the distribution chain and stock control; 2) technologies which can extract value from food waste by facilitating its use as animal feed, crop fertilizer or ingredients (neutraceuticals), which can be extracted for benefit in the food or pharma sectors.

Synthetic Biology

4.47 With the genomics revolution and rise of systems biology in the 1990s came the development of a rigorous engineering discipline aiming to create, control and programme cellular behaviour. The resulting field, known as synthetic biology, involves the design and construction of novel artificial biological pathways, organisms or devices, or the redesign of existing natural biological systems (Cameron *et al.*, 2014). According to these authors, the technology has experienced dramatic growth over the past decade and is poised to transform biotechnology and medicine (Cameron *et al*., 2014). As the technology is based on the use of glass or plastic vats (bioreactors), and needs only sun or sugar, algae and nutrients, it can be located anywhere (Policy Horizons Canada, 2014).

4.48 Although currently at a very early stage in its development, synthetic biology has the potential to drive industry, research and employment in the life sciences in a way that could rival the development of the computer industry from the 1970s to the 1990s (Government Office for Science, 2012). The global synthetic biology market is expected to reach $16.7 billion by 2018 (Policy Horizons Canada, 2014). It is clear that even at this early stage, synthetic biology offers considerable opportunities, but there are also concerns around potential misuse, in particular the generation of novel pathogens or modification of existing ones to increase virulence or defeat medical countermeasures (Cameron *et al.*, 2014).

4.49 Many commentators consider that synthetic biology may well be the most disruptive of all the technologies considered in this document. Industries that may be disrupted include pulp and paper, building materials, chemical manufacturing, pharmaceuticals, **agriculture and food,** and fossil fuel extraction. Disruption could be so extensive and pervasive in the sense that the application of synthetic biology could create a scenario in which secondary-processing companies could bypass the primary producers and develop self-sufficient factories that grow raw materials to their exact specifications using bioreactors and locally available feedstock (Policy Horizons Canada, 2014).

4.50 Synthetic biology includes a range of approaches, from top-down redesign of whole bacteria, to bottom-up assembly of new species (although this has yet to be achieved). The concept that has shown the greatest early promise is fashioning bacteria into 'biofactories' to produce specific chemicals or biological compounds. For example, the Lawrence Berkeley National Laboratory in the USA has engineered bacteria to produce artemisinin, a compound used to treat malaria. When genetic engineering was used to develop a yeast to produce precursors to artemisinin, it took 150 person-years of work and $25 million. Using synthetic biology, however, a laboratory of 12 people produced 12 biological systems of comparable complexity in three months (Government Office for Science, 2012).

4.51 Foresight Canada (2012) foresees that in 2028 synthetic biology will have the potential to produce different kinds of food, including meat and drinks, at lower costs than today. By manipulating genes, brand-new foods can be created with new properties or flavours. The same source also forecasts that the bioproduction industry is expected to reach $100 billion by 2020 alone. As well as different kinds of foods, new tailor-made microbes can have new capabilities, e.g. growth on different substrates, resistance to stress/attack by phage, production of health-promoting bioactives, inhibition of undesirable microbes etc.

4.52 While application of this new technology is deemed to offer great benefits by making possible new drugs, renewable chemicals or clean energy, commentators also raise concerns about safety, environmental and socio-economic risks. There are also huge concerns surrounding any technology which can 'create new life', – particularly in the absence of a well-tested regulatory framework. On the opportunity side, life replicates itself for free, input costs are low, and manufacturing more biological devices involves only using more feedstock. Progress in synthetic biology could mean the beginning of a different world that moderates today's concerns over issues like resource depletion and energy supply.

Conclusion

4.53 We have barely scratched the surface of what biotechnology can and will do to change agricultural production and products during the period covered by this Foresight. Our ability to manipulate genes will become faster, cheaper and more accurate. The science of biotechnology will converge with genomics, bioinformatics, and nanotechnology. The resulting innovations will encompass all three elements of sustainability – economic, environmental and social. Some innovations will be focused on production, others on reducing environmental impact and still others on health. Traits will be stacked and intellectual property will be mixed in many ways, resulting in most of our agricultural and food products most likely being impacted in some way by biotechnological applications in the decades ahead.

4.54 However, there are significant politico socio-economic barriers to be overcome, particularly in the EU, before some of the possible biotechnological solutions are adopted. Issues of environmental threats, food safety and consumer acceptance arise in respect of a number of these technologies. These matters can only be addressed by high quality research programmes, effective policy development and continuous communication with consumers.

4.55 Given the public good nature of these issues, public sector RTD agencies have a primary role to play in developing credible, transparent and well-communicated risk analyses in regard to the new technologies. While new technology will be necessary in addressing the food security and environmental challenges confronting food producers, technology alone is not sufficient: technology innovation must proceed in a broader context which fully addresses the health and environmental risks which new technologies may give rise to.

4.56 As the relevant public research agency in Ireland, Teagasc has a responsibility to consider its approach to these challenging new technologies on behalf of Irish producers, consumers and policymakers. This is a key underlying motive in setting out on the Foresight project.

5. Digital Technologies

> **Over the next decade, emerging digital technologies such as data analytics, sensors and artificial intelligence will transform or replace many products, processes and jobs. They will enable new kinds of tools and processes for co-creation, co-production, co-monitoring and co-consumption. They will fundamentally affect established roles and responsibilities among societal actors, and may even change how we define government, business and civil society.**
>
> **Policy Horizons Canada, 2012**

5.1 Access to timely information has become essential for farmers around the world. This includes accessing weather, market prices and general advisory information on products, equipment and techniques. The advent of computers, development of the Internet and the universal availability of mobile phone technology have all greatly facilitated farmers' access to countless information sources.

5.2 ICT is already being applied extensively within the agricultural and food industries for both improved efficiency and productivity. In addition, the application of digital technologies is increasingly reforming established marketing structures within the food by increasing the number of global players.

5.3 Research and development into the further integration of digital technology and agricultural productivity continues, with researchers and manufacturers investigating new ways to utilize ever increasing computing power and more accurate sensors. It is not inconceivable to envision a scenario in the not-too-distant future in which a huge range of agricultural tasks will be undertaken by autonomous robots and all crop plants will be monitored and managed on an individual basis.

5.4 Further growth of the rural digital economy is being facilitated in many countries by both the rollout of a next generation network broadband and the growing impact of the digital economy in many other economic sectors. The digital economy is "the global network of economic and social activities that are enabled by platforms such as the internet, mobile and sensor networks" (CSIRO, 2013).

5.5 The real significance of improved broadband services in rural areas lies in the complementarities that are made possible arising from the simultaneous developments in related technologies. These include (CSIRO, 2013):

- Sensor technology systems that are increasingly low cost and widespread, creating an "**internet of things**" where a growing number of "things" such as pasture vegetation, soil moisture, livestock movements and farm equipment can be monitored.
- The availability of spatially-enabled, mobile sensing technologies for characterising farm-scapes (e.g. identifying soil groups) and measuring changes in biomass.

- Smart personal devices that make accessing information on the move easier, and the development of easy-to-use and fit-for-purpose apps.

- Cloud computing technology that simplifies access to, and sharing of, information and applications, thus removing many of the requirements for on-farm computing systems.

- New interfaces (voice and gesture control) will continue to be perfected, and coupled with AI systems, these will increase the penetration of this technology in farms.

- Increasing ease of use of video-conferencing systems that are personal and can be used in the field through low-cost personal devices or dedicated video monitoring services. This could facilitate the rise of “remote farming”-managing farmland from a distance.

5.6 One area where many of these digital technologies have come together for the benefit of agriculture is that of ‘Precision Agriculture’ (PA). The development of the Global Navigation Satellite Systems (GNSS) has permitted the semi-automation of various farming vehicles and, in conjunction with developments in electronic sensor technology, has led to the development of PA.

Precision Agriculture

5.7 According to the EU (2014), “Precision Agriculture (PA) is a whole-farm management approach using information technology, satellite positioning (GNSS) data, remote sensing and proximal data gathering. These technologies have the goal of optimising returns on inputs whilst potentially reducing environmental impacts”. Recent research results suggest that PA will be one of the ten key breakthroughs in the next ten years (CSIRO, 2013).

5.8 Precision agriculture is an information-based decision-making approach to farm management designed to improve the agricultural process by precisely managing each step and managing variation in crops, soils and animals. In this manner, PA can provide a management approach optimizing both agricultural production and profitability. Additionally, part of profitability can come from the optimised use of inputs (machinery, labour, fertilizer, chemicals, seeds, water, energy, etc.), leading to both cost savings and also environmental benefits.

5.9 Today, the technological infrastructure of PA in terms of positioning and machine control systems is well developed and the conceptual use in terms of potential improved management is well understood. However, there are still significant research research/development deficits in: understanding causes of variation in crops; sensing crop and soil characteristics accurately, intensively and inexpensively; understanding the causes of variations; combining data sources/streams (animals and crops); developing appropriate management responses.

5.10 PA is a farming management concept based upon observing, measuring and responding to inter and intra-field variability in crops, or to aspects of animal rearing. The potential benefits mainly arise from increased yields and/or reduced costs through more specific/precise/targeted inputs or management actions. Other benefits come from improved mechanisation efficiency, better working conditions, improved animal welfare and the potential to improve various aspects of environmental stewardship. Thus, PA contributes to the wider goal concerning sustainability of agricultural production (EU, 2014).

5.11 On large scale farms, the improved precision of positioning and machine control technologies has led to steering-aid technologies and headland management systems that ease the operators' task, increased machine efficiency and offer scope for controlled traffic farming where soil structure impacts can be spatially limited. Also positioning and performance information, coupled with telematics data transfer, offers scope for cloud-based data capture about machine and/or crop performance, which is useful in larger machine fleet management. While these systems are currently only economically beneficial on larger farms /machinery operations, it's likely that cost will decrease making their application more universal.

5.12 While machine guidance technology and machine management technologies have improved rapidly, leading to re-surged interest in PA, the success of variable rate application methods, where inputs are applied in response to measured variability, is much less certain, with very real challenges in understanding the causes of and responding to measured variability continuing.

5.13 PA is also applicable in the context of livestock farming, where it is referred to as Precision Livestock Farming (PLF). It may be described as an individual animal management concept based upon observing, measuring and responding to the animal and the interaction of the animal to its environment. It has been typically applied to the more intensive husbandry of pigs and poultry in the past. However, its relevance and application in dairying is now recognised and is progressing at a rapid rate. Processes suitable for the PLF approach include animal growth, milk production, cow nutrition from grass, the critical points in the dairy cycle that influence production efficiency, e.g. animal fertility, reproduction, genetics, detection and monitoring of diseases, aspects related to animal behaviour and animal welfare.

5.14 The advance of sensing, monitoring and control systems has led to the development of automatic milking systems (AMS), now being marketed by several European manufacturers. In the absence of the daily individual animal contact associated with conventional milking, AMS systems typically use a number of sensors to monitor animal health and production. Sensing systems (movement, temperature etc.) can be used independent of MAS systems; some may be simple birthing detectors while others use the density of data and complex analysis algorithms to predict, birthing, oestrus, lameness, feeding and other health issues. These communicate management alert communication to the farmer via SMS or phone app.

5.15 When the concept of precision agriculture, specifically spatially variable management, was in its infancy 25 years ago, there were huge expectations and large research programmes focused on exploiting the technology. However, the challenges of understanding and responding to the causes of crop variation largely remain, as complex physical and biological processes (in soil, plants and animals) are involved.

5.16 New sensor technology is key to understanding soil, plant and animal variation. Sensors must reliably and adequately measure key soil crop and animal parameters at a resolution suitable for reliable analysis and suitable for an appropriate management response. Sensors may be satellite, UAV or, more typically, field-machine based. Sensor development is a significant task, but progress is being made.

5.17 Once variation in soil crop or animal is measured, the appropriate management response is necessary. This may be simple in the case of a soil nutrient deficiency or animal health issue, however it is usually much more difficult where poor growth indices (NDVI or crop yield) is from a difficult-to-determine cause and, consequently, management decisions are extremely challenging. As more sensor information becomes available, the need for research-based management responses will increase.

Big Data

5.18 Sensors, imagery, and other technologies referred to above are capable of generating huge quantities of data on individual farms building up potentially large databases of information sometimes referred to as ‘Big Data.’ Big Data refers to both the large volumes of data with high levels of complexity now accumulating and the analytical methods applied to them which require more advanced techniques and technologies in order to derive meaningful information and insights.

5.19 Part of this increase in data comes from the global network of Earth Observing Satellites. New advancements in small satellites will lead to multiple observations a day at high resolution of Ireland within a decade. The rapidly decreasing cost of development and deployment of these micro-sats means it is likely that Ireland (either state or private) will have in-orbit assets by 2040.

5.20 Big data (and analysis thereof) also relates to DNA sequence data to study gut microbiota composition of humans (and animals) with a view to its modification through diet in a beneficial way: the study of host genomes and transcriptomes to facilitate the development of personalised nutrition (again also relevant to animals).

5.21 A smart use of big data in agriculture has the potential to increase productivity, food security and farmer incomes. This will involve the development of sensors and complex analysis of big data, but it will particularly have to be underpinned by a complex understanding of the complex biological processes involved in soils, plants and animals. Through an intelligent and widespread use of data coming from sensors, farming methods could be transformed for the better, including a more efficient use of natural resources in farming practices (CSIRO 2013).

5.22 At the individual farm level, more precise data will increasingly be used to provide evidence of compliance with regulatory and quality assurance and traceability requirements. At an aggregated level, use of Big Data will facilitate benchmarking, enabling farmers to compare their own performance with local, regional and national averages. Properly pooled, structured and mined, large datasets can also assist the research community by identifying new areas for research, development and innovation.

5.23 Big data by its sheer volume of information offers a number of opportunities for precision agriculture. Where single sensors can fail to predict meaningful soil or biological characteristics, when the data from a number of sensors which individually have weak predictive ability, is combined, they may more accurately predict the target characteristic. At the most rudimentary level, data can be analyzed in real-time to flag critical values which are important for production decision-making. At a more sophisticated level, high resolution spatial maps of soil moisture can direct the efficient use of irrigation. Similarly, detailed maps of pest damage can allow for the precise targeting of controls in a field. At the most advanced level, remote-sensed data, coupled with measurements made with sensors on machines, or arrayed on the ground, can be processed to create a dynamic, three-dimensional picture of soil, plant and environmental properties in a field. This picture would be composed of many layers of data, which singly or together can support specific management decisions.

5.24 Big data will increasingly become part of precision agriculture and when supported by appropriate research to drive useful actionable information, will influence farm production decision-making in the not-too-distant future. However, there is a significant research challenge as well as a steep learning curve on the part of agricultural stakeholders to ensure correct decision-making based on big data. There will also need to be a strategic shift in governance and policy making as a result of the application of big data approaches.

Robotics

5.25 Robots acting independently of human control – which can learn, adapt and take decisions – will revolutionise our economy and society over the next 20 years (Willets, 2013). Using robotics, farming has the potential to become far more resource-efficient and environmentally friendly. Flying drones with appropriate sensors could monitor large fields quickly and precisely. With information from sensors on drones, satellites and ground-based equipment, the logical development is to have an automated managed response delivered either by an automated machine with some manual control or a fully automated robot.

5.26 As the difference between full robots or process controlled actuators on a machines is largely academic; the concept that a management action or response can be automated to give either more precise/accurate control of some process, or eliminate human effort or error, is the significant step. For example, the field response to crop sensing in terms of varying input application may be delivered by a conventional tractor with a fully automated fertiliser spreader/ crop sprayer, or, less likely, by a fully robotic automated tractor. Full robotics will be used in certain processes, e.g. automated milking systems etc. Robotic pickers will continue to emerge and, in time, be able to harvest more types of crops.

3D Printing

5.27 3D printing, —also known as additive manufacturing, — allows highly customized parts and products to be printed on demand anywhere. It is already being used to produce a wide array of products from furniture and clothes to auto, airplane and building parts. Boeing is working on printing airplane wings without rivets. R&D efforts are increasing the capability to print with a growing number of materials, allowing for ever increasing sophistication of the products that can be made with 3D printing.

5.28 Over the next decade, more and more consumers will have a say in product design, and the production of increasingly complex products will decentralize. Early in the coming decade, 3D printing will enable forward-looking entrepreneurs to integrate it in existing processes; later in the decade, it will be in many homes and dramatically shorten value chains for a growing range of consumer goods (Policy Horizons Canada, 2013).

5.29 3D printing allows for distributed manufacturing on demand, acting as a counter to off-shoring and centralising urban-centred forces in current manufacturing trends.

5.30 This kind of technology will lead to new types of production systems for the manufacture of complex multi-material products. Applications for this can be found among a whole range of sectors like electronics, solar cells, lighting and **food.** TNO, Netherlands, has already demonstrated 3D food printing drawing on its knowledge of mechatronics, 3D industrial printing and specific food knowledge in the areas of ingredients, formulae, texture and structure. Some US institutions and private companies have also used the process for creating food products.

Conclusion

5.31 Farming has the potential to become far more resource-efficient and environmentally friendly on existing farmland by developing more targeted and precise management systems. This requires the development of appropriate sensing technologies and developing specific management responses facilitating a more precise and accurate management technique. While technologies such as positioning, robotics and machine control systems are key to this development, the essential components are development of appropriate soil, animal and crop sensors; data analysis and delivery of appropriate response based on a fuller understanding of the complex physical (soil) and biological (soil, animal and crop) processes that underpin agricultural production.

5.32 Artificial intelligence (AI), sensors, data analytics and robots will be key components of significant change in many workplaces around the world. These technologies will transform many jobs where a routine physical or mental task is repeated; AI will increasingly handle the routine, while workers will be free to focus on the exceptions that AI cannot handle. AI and data analytics will also increase productivity and the demand for non-routine and professional skills by reframing the way we design, coordinate, manage, deliver and assess products and services. Sensors will provide workers with a much broader picture of the processes they manage, improving efficiency and client satisfaction. Cheaper, mass-produced robots and autonomous delivery vehicles will change the flow, timing and flexibility of work.

5.33 The interconnectedness of the modern farm will allow farmers to sell more than produce. Data itself can be valuable. By 2040, we are likely to have moved significantly toward a “post petroleum” world with electric cars replacing petrol for instance. In this environment, it’s possible that farms will generate much of the energy they need on farm (improved wind and photovoltaic systems) and sell excess energy to the grid. Electric machinery will be more common on farms, as batteries become more energy dense. This interconnectedness will be continent-wide and will drive expansion of Irish farm enterprises abroad.

5.34 Data can be vulnerable- data protection and system hardening will be as important in food traceability in modern farms as bio-security is now (can you demonstrate that the automated systems producing this food were secure?).

6. Nanotechnology

We are moving to a world of <u>radical abundance</u>, where nanotechnology will help to produce radically more, while consuming radically less.

K. Eric Drexler, 'the founding father of nanotechnology'

6.1 Nanotechnology has emerged as a technological advancement with the potential to develop and transform the entire agri-food sector, offering opportunities to increase global food production, in addition to improving its nutritional value, quality and safety, as well as reducing waste. However, there is concern over safety and regulation of the technology, which may inhibit its widespread uptake by the agri-food industries, at least in the short-to-medium term (EU Joint Research Centre, 2014). Concern also exists in relation to industry and consumer acceptance (Handford et al, 2014).

6.2 Nano/microtechnology has the potential to enable significant developments in food processing, including the development of targeted production and delivery systems (encapsulation/emulsification), new sensors for detection of pathogens, toxins and contaminants, e.g. drug residues (enabling advanced process control and quality monitoring), as well as advanced packaging materials with unique barrier or microbial growth-inhibiting properties (STOA, 2009). Sensory benefits in terms of taste, texture and consistency are also possible (Sekhon, 2010).

6.3 The technology also makes possible the development of advanced food processing tools and equipment for mixing and homogenisation, separation, fractionation and structure forming. As most of the mechanisms for structure formation in foods take place at micrometer scale, such new process technologies are intrinsically more energy efficient, and make better use of available raw materials. For emulsification and fractionation, the feasibility of this approach has already been demonstrated in practice. Other applications are still under development (STOA Summary p4)

6.4 The area of food packaging has witnessed a huge amount of innovation in recent years, including in barrier improvement, with the use of various nanoscale fillers. This has also resulted in reduced impacts by targeted accelerating of the factors of spoilage and contamination. Intelligent packaging is the new generation of packaging. Many such packaging systems incorporate sensors and sometimes nanosensors. With the aid of these sensors, information about the food can be communicated to the consumer or the system can react to the information and change conditions within the packaging to delay spoilage/contamination (Cushen *et al.*, 2012).

6.5 The application of nanomaterials in agriculture aims, in particular, to reduce applications of plant protection products, minimize nutrient losses in fertilization, and increase yields through optimized nutrient management (EU Joint Research Centre, 2014). There are many other potential opportunities for nanotechnology to play an important role in agriculture and food production, including in livestock production.

Examples include development of rapid, on-farm diagnostic technologies (either at individual or herd level) to inform sustainable animal treatment plans and disease prevention strategies, such as vaccination. Such applications will assist greatly in the development of targeted treatment strategies which will lead to more sustainable use of antibiotics and anthelmintics. Nanotechnology will also play a role in vaccine development with the introduction of novel nano-vaccines. Application in livestock production includes nanobiosensors for animal disease diagnostics and improved efficacy and nutrition of animal feeds (Handford et al, 2014).

6.6 Productivity enhancement through nanotechnology-driven precision farming and maximization of output and minimization of inputs through better monitoring and targeted action is desirable for economic and environmental reasons. Nanotechnology enables plants to use water, pesticides, and fertilizers more efficiently. Anticipated applications include nanosensors/nanobiosensors for detecting pathogens and for soil quality and for plant health monitoring; nanoporous zeolites for slow-release and efficient dosage of water and fertilizers for plants; and of nutrients and drugs for livestock; nanocapsules for agrochemical delivery; creating biofuels; nanobiosensors for identification of pathogen contamination and improving plant and animal breeding (Chen and Yada, 2011) .

6.7 Despite these potential advantages, nanotechnology has found very few market applications to date in the agricultural sector, in contrast with other sectors. The potential of nanotechnology in agriculture is large, but a few issues are still to be addressed, such as increasing the scale of production processes and lowering costs, as well as risk assessment issues (EU JRC, 2014).

6.8 The emergence of nanotechnology applications in consumer products has also raised a number of ethical and societal concerns in some countries, starting from health and environmental safety, and ranging to consumer perception and intellectual property rights. The challenge for the future consists in ensuring that the benefits of the technology are not counteracted by possible human and ecotoxicological risks, such as the potential migration of nanoparticles into the brain and unborn foetus, for instance.

6.9 As with many new technologies, being enthusiastic in the rush to market may distract from the importance of the investigation of possible health and environmental implications. The scientific community must learn from previous introductions of new technologies, being particularly sensitive in the food area. For example, genetically modified foods were not well received by consumers because there was a perceived risk associated with them. Thorough risk assessment of nanotechnologies in the food sector should provide a sound foundation on which commercial products can be launched with confidence, or withdrawn to protect consumers and the environment from potential hazards (Cushen *et al.,* 2012). Research has demonstrated some of these risks and the scientific community is concerned. It is not just consumers who are. There are scientific knowledge gaps that need to be addressed. Risk assessment will not be a simple exercise in some cases.

7. Chemistry, Physics and other Science-Based Technologies

Fundamental discoveries in physics dominated the first half of the 20th century, whereas discoveries in molecular biology, such as the structure of DNA, dominated the second half. The 21st century may well bring forth a new era, one of revolutionary discoveries in materials research that result in far-reaching changes for society and how we live.

Adams, J and Pendlebury, D (2011)

7.1 Science and technology together provide the foundation for driving innovation to continually improve our quality of life and prosperity. Major breakthroughs in chemistry, physics and other sciences are required to solve current and future societal challenges in health, food and water, and energy. The solutions will require breakthroughs originating from a combination of advances in understanding and new techniques, as well as major and sometimes unpredictable discoveries.

Chemistry and Chemical Technologies

7.2 Matching energy and food demand with limited natural resources without permanently damaging the environment is the greatest technological challenge facing humanity. Chemistry and engineering are a key part of the solution. Many opportunities exist for the chemical sciences to assist in supplying healthy, safe and affordable food for all. The main challenges concern agricultural productivity, water, healthy food, food safety, process efficiency and supply chain waste.

7.3 Through the development of fertilizers, plant growth regulators and pesticides, the chemical sciences drove many of the advances in the 'green revolution' — an unprecedented expansion of agricultural production that helped to feed the world's population while it grew from 1.7 billion to 6 billion during the 20^{th} century. They have also contributed to new technologies for food processing, preservation and storage, which facilitated the development of global food markets. Explorations of the chemical content of foods and the chemistry of metabolic processes also underpinned advances in our knowledge of the relationship between diet, nutrition, metabolism and health.

7.4 Chemistry will continue to play a key role in terms of new technologies and knowledge needed in **agricultural productivity** (new products and formulations in pest control and fertilisers, improved understanding of nutrient delivery and uptake); **effective farming** (development of biosensors, vaccines and veterinary medicines); **healthy food** (foods with improved nutritional content); **food safety (**new technologies to help detect food-borne diseases as well as developing precautionary techniques); **process efficiency (**manufacturing, processing, storage and distribution of food needed to ensure minimum wastage and maximum efficiency).

Materials Science and Technology

7.5 Materials Science and Engineering (MSE) is concerned with the creation of materials with novel properties and their use in a variety of fields ranging from ultra-fast computer chips and high-efficiency solar cells to high-powered jets, and even food packaging Today, engineering innovations are increasingly dependent on breakthroughs in materials at the micro- and nanometer scale.

7.6 The use and development of materials has constituted a major current in the history of mankind. The history of technology is replete with important examples of revolutionary change brought on by the discovery of new materials and new uses for materials. Bronze gave way to iron, then to steel and arguably now to silicon. Will graphene replace silicon in electronics? Will cars be fuelled by hydrogen stored in MOFs? Will stem cells grown on nanofibrous scaffolds make organ replacement routine? These questions tend to suggest that we may now be entering a distinctly new Age of Advanced Materials (Adams and Pendlebury, 2011).

7.7 Package design and construction play a significant role in determining the shelf life of a food product. The right selection of packaging materials and technologies maintains product quality and freshness during distribution and storage. Materials that have traditionally been used in food packaging include glass, metals (aluminum, foils and laminates, tinplate, and tin-free steel), paper and paperboards, and plastics. Moreover, a wider variety of plastics have been introduced in both rigid and flexible forms. Today's food packages often combine several materials to exploit each material's functional or aesthetic properties..

7.8 Research and development of bio-nanocomposite materials for food applications such as packaging and other food contact surfaces is expected to grow in the next decade with the advent of new polymeric materials and composites with inorganic nano-particles (Sorrentino, et al., 2007). The challenge for the future consists in ensuring that the benefits of the nanomaterials used are not undermined by possible human and ecotoxicological risks, such as the migration of toxicologically critical nanomaterials of food packaging into food, for instance (STOA, 2009).

Physics

7.8 The study of the physical properties of soil has fundamental place in the application of science to agriculture. It occupied an important position in the early days of agricultural science, and, after a lengthy eclipse in the latter half of the nineteenth century, it again came into prominence, owing to the recognition of the colloidal properties of the soil. The older concepts have been examined from this point of view, and it appears that the soil must be regarded not as a mass of comparatively inert grains over which water is distributed in a thin film, but as particles the surface of which is coated with colloidal material. The composition of this material is complex.

7.9 The extent to which we can conserve the earth's soil resources and exploit them for the good of mankind is dependent on our knowledge of this dynamic and biologically diverse material. In the past century much has been learned about soil through the application of the chemical, physical and biological sciences. The land management practices that we have in today's modern and highly productive agriculture are the outcome of evolving science-based studies of the soil, which we must continue to build on into the future.

8. Agriculture and Food Technologies

8.1 The STOA (2013) report on *Technology Options for Feeding 10 Million People,* suggests that European (and Irish) agriculture must address the following priorities:

1. Maintain and improve its own productive resources so that agriculture can remain robust and potentially capable of contributing more to meeting future food security needs
2. Increase the emphasis on resource efficiency to enhance both productivity and sustainability
3. Promote innovation and the dissemination of best practice as well as traditional research and development
4. Reduce demand in Europe over time both for the raw materials required for production as well as for agricultural commodities and processed foods
5. Align Europe's bioenergy policies with long-term strategies regarding food, agriculture and biodiversity
6. Support sustainable agricultural production in the developing world.

8.2 These priorities reflect the need for future food production to face up to known future challenges as well as the many possible additional uncertainties which could have a significant impact on the development of our food system in the long term. For example, climate change may impact on agriculture in ways that we have not so far considered. Limitations on nutrient supplies, particularly phosphates, could present very serious challenges and constraints. Outbreaks of disease could have a significant impact. All of these challenges alert us to the need to begin the process now of building sustainability and resilience into our systems.

Developing more Sustainable and Resilient Farming Systems

8.3 Developing more sustainable and resilient food production systems will require the inputs of many of the generic technologies discussed above. It will also need the identification and active dissemination of current best practice and accumulated knowledge, as well as the further refinement of those practices.

8.4 Scientific research underpins this by providing the necessary technologies and an understanding of some of the processes involved. However, such research must be combined with research from other disciplines, be placed in a wider context, be demonstrated in farming practice and involve the decision makers themselves if it is to help ensure adequate and sustainable food production in the future. This holistic systems research perspective is often neglected in agricultural research.

8.5 The Royal Society (2009), and the Government Office for Science (2011) called for the joint application of new technologies along with traditional agricultural technologies to achieve sustainable intensification. "A pluralist research portfolio is essential: the magnitude of the challenges is so large that no single research avenue will address all the new knowledge required.” (Government Office for Science, 2011). This highly influential report asserts that no techniques or technologies should be excluded from consideration: a diversity of approaches is needed in order to address the differing requirements of specific enterprises, localities, cultures and other circumstances. Such diversity demands that the breadth of relevant scientific enquiry is equally diverse, and that science needs to be combined with social, economic and political perspectives (Government Office for Science, 2011).

8.6 This importance of bringing together the new technologies with longer-established agricultural technologies and practices can be illustrated in many areas. The concept of Precision Agriculture, for example, involves the application of many rapidly developing technologies; however, unless these are linked with the complex biological processes involved in the production of crops and animals, the gain achieved will be limited.

8.7 Similarly, to ensure sustainable productive capacity, a key resource which must be protected and requires specific consideration in agricultural production, is the soil. A greater understanding of the functioning of the soil and the impacts of management such as soil cultivation, intensive annual cropping and compaction from animals and machines, illustrates the need to mobilise and focus the technologies discussed in this document onto a complex but key resource on which agriculture’s production depends.

8.8 Farmers worldwide must rise to this challenge by adapting their farming systems to meet changing circumstances, taking up established and new technologies and practices as necessary to provide the best mix of outputs with minimum use of non-renewable inputs. Adapting their farming systems may also include the enhanced use of local and natural resources, promoting ecological resilience and identifying and enhancing the provision of ecosystem products and services (Dobermann & Nelson, 2013). To do this, landowners will need the right information at the right time and in the right form to support their decision making, e.g. the use of mapping and remote-sensing to identify ecosystem products and services; the identification of critical source areas through the use of LiDAR and digital elevation models (DEMs).

8.9 Dobermann and Nelson (2013) identified the following good agronomic management principles in the context of agro-ecological intensification of crop production:

- Profitable and sustainable crop rotations
- Choosing quality seed of a well-adapted high-yielding variety or hybrid that also meets market demands
- Planting at the right time to maximize the attainable yield by capturing light, water and nutrients
- Maximize the capture and efficient utilization of available water

- Integrated soil and nutrient management, including conservation agriculture, balanced and more efficient use of fertilizers, as well as utilization of available biological and organic sources
- Integrated pest management, including the use of functional biodiversity, biological control and the judicious use of pesticides
- Harvesting at the right time
- Optimize recycling and use of biomass and agricultural by-products
- Where suitable, enhance crop-tree-livestock interactions).

Soil and Ecosystem Services

8.10 Natural resources, especially those of soil and ecosystem services, are fundamental for the structure and function of agricultural systems and for social and environmental sustainability, in support of human life. Ecosystems and the biological diversity contained within them provide a stream of goods and services, the continued delivery of which remains essential to our economic prosperity and other aspects of our welfare. The benefits of these services manifest themselves at local, regional and global scales with often conflicting demands between stakeholders at these different levels.

8.11 Agro-ecosystems contribute substantially to the supply of ecosystem services and their continued success in this regard depends on the management of those systems. Expansion and intensification of agriculture can have significant negative impacts on the provision of ecosystem services for private and public use (Foley *et al.*, 2005). Counteracting this requires the development and implementation of more productive and sustainable production systems.

The Social and Economic Sciences

8.12 The introduction of new agricultural technologies can have complex social and economic consequences, both for people in the immediate farming area and more distant groups, through markets for land, labour and physical inputs and outputs. Beneficial technologies and techniques can take time to filter through to farmers and to expand into widespread practice. If new technologies are introduced without consideration of infrastructure, institutions, markets, cultures and practices, success can be short-lived or there can be serious unintended consequences. New technologies typically offer greater or lesser benefits depending on scale, and often benefit larger-scale farmers more than smallholders.

8.13 In all agricultural systems, there are producers of various sizes and incomes, with different levels of knowledge. New technologies are often taken up first by those farmers with access to sufficient money and information to be able to take a risk by trying something new. These early adopters may then benefit from productivity gains or lower costs, putting pressure on their poorer competitors.

8.14 Technologies can therefore widen the gap between farmers. Farmers' knowledge is a vital asset that needs to be brought into the process of designing more productive farming systems. Farmers have their own understanding of soils, climate and the use of different agricultural practices in their geographic location. These need to be part of the search for solutions for improved crop productivity and more resilient agro-ecological systems.

8.15 The Social and Economic Sciences will continue to have a key role to play in ensuring that all new technologies are introduced on the basis of good evidence and thereby help to ensure better take-up by end users.

Energy

8.16 Rising energy prices over the past decade, along with evolving policies promoting renewable energy and on-farm conservation practices, have transformed the relationship between the energy and agriculture sectors. Traditionally, agriculture used energy both directly in the form of fuel and electricity and indirectly through use of energy-intensive inputs, such as fertilizers and pesticides. However, since the mid-2000s, rising energy prices and expanding biofuel policies have greatly increased the demand for agricultural products as renewable fuel feedstocks. As of 2012, corn-based ethanol and soybean-based biodiesel supplied almost 6 per cent of U.S. transportation fuels, consuming 42 and 1 per cent of U.S. corn and soybean production, respectively (Beckman, *et al.,* 2013).

8.17 Contemporary food systems are heavily dependent on non-renewable energy resources, including both direct and indirect life cycle inputs. Relationships between energy-dependent inputs and food system productivity are complex and nonlinear. In some cases, diminishing returns are obvious, whereas in others, increased energy use is warranted to improve energy return on (energy) investment ratios (Pelletier, N. *et al.,* 2011). Considerable opportunities exist for improving energy efficiencies, but the scale of food system energy use globally will likely continue to increase due to population growth and changing consumption patterns.

8.18 Energy efficiency must be considered from a variety of perspectives, including both anthropocentric and ecological perspectives. Whereas the main focus of research on energy use in food systems has been on non-renewable energy resources, increased attention must focus on biotic energy use efficiency, in particular, with respect to biodiversity objectives. In light of the volatility of energy prices and uncertainties in regard to long-term fossil energy availabilities, the energy intensity of food systems has important implications for food security.

8.19 The bioenergy market is an important segment of the renewable energy sector. Important and challenging EU and national targets now exist to develop renewable energy in response to concerns about climate change and energy security.

8.20 The quantity of existing biomass resources in Ireland is limited. There is a significant shortfall in the amount of biomass needed to meet Government 2020 targets for bioenergy. The question remains as to how much of this shortfall can be made up from non-food crops and whether there is a viable future for farmers in non-food crop production.

8.21 A vibrant non-food crops industry here would certainly provide farmers with added income streams. However, the degree to which the bioenergy targets will be met from locally produced non-food crops remains to be seen and depends on a number of factors including evolving bioenergy policies and supports as well as developments in new technologies. Given a favourable environment for development, Irish farmers can make a substantial contribution towards meeting Government targets and policies in the bioenergy and non-food crop sector.

Food Technologies

8.22 The food and drink industry is the EU's largest manufacturing sector in terms of economic turnover, people employed, and number of businesses. It has an important role to play in achieving a more sustainable food system, not least by creating more resource efficient manufacturing and distribution businesses. This involves not only reduced wastage and more sparing use of inputs, including water and energy, but also attention to food quality and optimal control of ambient conditions in which the food is stored and transported (temperature and humidity). New technologies are available for this purpose. Much can be achieved by improving food chain management and communication, including the use of modern risk-management and operational excellence tools and systems. There is a common assumption that processes in the EU are already efficiently streamlined, but the innovation leaders in the industry are showing that significant savings can be made (STOA, 2013).

8.23 The food and drink industry is underrepresented in R&D expenditures compared to other manufacturing sectors. In 2009, the R&D investments for the whole sector were 0.53% of the annual turnover, which leads to the classification "low intensity R&D sector" on the European industrial R&D investment scoreboard (JRD/DG RTD, 2012). The big food producing companies are responsible for the major part of the R&D expenditures of the sector. The innovative power of SME's in the European food sector is only very limited, despite their large number. This distinguishes the food industry from other sectors like pharmaceuticals, ICT or biotechnology, where SME's are the driving force behind growth and innovation (STOA, 2013).

The Role of Education and Extension Services

8.24 Agricultural extension and advisory services are essential for closing the gap between actual and potential productivity and ensuring widespread adoption of more sustainable agricultural practices that preserve natural resources and provide crucial environmental services.

8.25 Extension and advisory services can provide farmers with information that allows them to make better and more informed choices about product mix, appropriate technologies and practices, and farm management. Too many farmers lack access to information from agricultural extension and advisory services. Smaller farmers are less likely than larger ones to have such access.

8.26 Strengthening the capacity for innovation means investing in learning and developing the skills of multiple actors in the agricultural innovation system. It also requires providing the right incentives to encourage people to put these skills into use and to develop the right attitudes and practices.

8.27 Education and training represent an investment in people and are probably the most important way to develop people's skills and competencies for innovation, whether they are farmers, service providers, researchers or policy-makers. Farmers need to attain more advanced levels of education to make use of new ICT-based information sources and technical advice and to respond to new market opportunities and environmental change.

8.28 In addition to basic education, agricultural universities, vocational and technical colleges and farmer training centres also play a role in creating the human capital needed to modernize the sector. Agricultural education and training raises agricultural productivity by developing producers' capacities and generating human capital for research and advisory services.

9. Conclusions

9.1 There is consensus amongst the results of food system models that, at the global level, one of the most critical drivers of future food supply is the rate of growth of yields due to new science and technology. New knowledge is also required for the food system to become more sustainable, to mitigate and adapt to climate change, and to address the needs of the world's poorest. These challenges will require solutions at the limits of human ingenuity and at the forefront of scientific understanding. No single technology or intervention is a panacea, but there are real sustainable gains to be made combining bio-technological, agronomic and agro-ecological approaches.

9.2 But technology alone is not sufficient: the context has to be provided whereby technology can build knowledge, networks and capacity (Kiers et al. 2008). Moreover, social concerns could seriously jeopardize even the judicious application of such new science and technology in providing enormous economic, environmental and social benefits. If this is to be avoided, technology innovation has to take fully into account the health and environmental risks to which new technology may give rise. Serious and rapid attention needs to be given to risk analysis and communications policy.

9.3 Another critical issue, particularly in the context of Irish agriculture, is the need to ensure the more universal uptake of existing technologies and practices. In a farming context in which many farmers, particularly in the beef and sheep sectors, do not employ existing best practices on their farms, the question could reasonably be posed as to the relevance of futuristic technologies in general in an Irish farming context.

9.4 While this is a reasonable question to raise on the basis of the evidence to date, many challenges are now coming into play which suggest that technology will have to be more widely adopted in future across all types of Irish farms. We are facing into a new era of global competition and new demands, both market and regulatory, will create a new context for Irish farmers.

9.5 Accordingly, Irish policy makers, scientists, farmers, food processors and consumers need to prepare for future technology. To do this well, they will need a clear understanding of how technology might shape the global economy and society, as well as their own sector, over the coming decades. They will need to decide how to invest in new forms of education and infrastructure, and figure out how disruptive economic change will affect comparative advantages.

Box 2 Appraising new technologies in the food system

- New technologies (such as the genetic modification of living organisms and the use of cloned livestock and nanotechnology) should not be excluded *a priori* on ethical or moral grounds, though there is a need to respect the views of people who take a contrary view.
- Investment in research on modern technologies is essential in light of the magnitude of the challenges for food security in the coming decades.
- The human and environmental safety of any new technology needs to be rigorously established before its deployment, with open and transparent decision-making.
- Decisions about the acceptability of new technologies need to be made in the context of competing risks (rather than by simplistic versions of the precautionary principle); the potential costs of *not* utilising new technology must be taken into account.
- New technologies may alter the relationship between commercial interests and food producers, and this should be taken into account when designing governance of the food system.
- There are multiple approaches to addressing food security, and much can be done today with existing knowledge. Research portfolios need to include all areas of science and technology that can make a valuable impact – any claims that a single or particular new technology is a panacea are foolish.
- Appropriate new technology has the potential to be very valuable for the poorest people in low-income countries. It is important to incorporate possible beneficiaries in decision-making at all stages of the development process.

Government Office for Science, 2011

9.6 In considering the disruptive potential of these technologies, we see that each could drive profound changes across many dimensions—in the lives of citizens, in business, and across the global economy. Many technologies, including advanced robotics, next-generation genomics, and renewable energy, have real potential to drive tangible improvements in quality of life, health, and the environment. Many of them could also change how and what consumers buy, or alter overall consumption of certain resources, including food. Others could fundamentally change the nature of work, both on the farm and in the food processing plant.

9.7 Almost every technology on our list could change the game for businesses, creating entirely new products and services, as well as shifting pools of value between producers or from producers to consumers. Some, like automation of knowledge work and the mobile Internet, could also change how companies and other organizations structure themselves, bringing new meaning to the anytime/ anywhere work style. With automation of knowledge work tasks, organizations that can augment the powers of skilled workers stand to do well.

9.8 As these disruptive technologies continue to evolve and play out, it will be up to farmers, business leaders, entrepreneurs, policy makers, and citizens to maximize their opportunities while dealing with the challenges. One thing is for certain, Irish agri-food businesses, both farming and processing, cannot in the medium-to-long term ignore these developments. The first step is for leaders to invest in their own technology knowledge. Technology is no longer down the hall or simply a budget line; it is the enabler of virtually any strategy, whether by providing the big data analytics that reveal ways to reach new customer groups, or the Internet of Things connections that enable a whole new profit center in after-sale support.

9.9 One clear message: the nature of work is changing. Technologies such as advanced robots and knowledge work automation tools move companies further to a future of leaner, more productive operations, but also far more technologically advanced operations. The need for high-level technical skills will only grow. Companies will need to find ways to get the workforce they need, by engaging with policy makers and their communities to shape secondary and tertiary education and by investing in talent development and training; the half-life of skills is shrinking, and companies may need to get back into the training business to keep their corporate skills fresh.

References:

Adams, J and Pendlebury, D (2011). Global Research Report: Materials Science and Technology. Thomson Reuters, Leeds.

Beckman, J. *et al.*, (2013). Agriculture's supply and demand for energy and energy products. Economic Information Bulletin No. 112, Economic Research Service, USDA, Washington, DC, USA.

Cameron, D.E. *et al.*, (2014), A brief history of synthetic biology**.** *Nature Reviews: Microbiology,* May 2014, 12, No 5, 381-390.

CSIRO (2013), *Smart Farming: leveraging the impact of broadband and the digital economy report*,

https://publications.csiro.au/rpr/pub?pid=csiro:EP137659

Cushen, M. *et al.* (2012), Nanotechnologies in the food industry – Recent developments, risks and regulation. *Trends in Food Science & Technology*, 24(1), 30-46

DAFM (2010), *Food Harvest 2020: A vision for Irish agri-food and fisheries,*

http://www.agriculture.gov.ie/agri-foodindustry/foodharvest2020

EC (2012). The EU Bioeconomy Strategy

EU (JRC) (2014), *Precision agriculture: an opportunity for EU farmers:*

http://www.europarl.europa.eu/RegData/etudes/note/join/2014/529049/IPOL-AGRI_NT%282014%29529049_EN.pdf

EU (JRC) (2014), *Proceedings of a Workshop on "Nanotechnology for the agricultural sector: from research to the field"*

http://publications.jrc.ec.europa.eu/repository/handle/JRC89736

FAO (2010), *Current status and options for biotechnologies in food processing and in food safety in developing countrie.* FAO International Technical Conference, Guadalajara, Mexico,

http://www.fao.org/docrep/meeting/019/k6993e.pdf

FAO (2012), *World agriculture towards 2030/2050: The 2012 revision*

http://www.fao.org/docrep/016/ap106e/ap106e.pdf

FAO (2014), *The state of food and agriculture. Innovation in family farming,*

http://www.fao.org/3/a-i4040e.pdf

Foley, J.A. *et al.,* (2005). Global consequences of land use, *Science* 309 (5734), 570574.

Garnett T *et al.,* (2013). Sustainable intensification in agriculture: premises and policies, *Science,* 34, 6141, 33-34.

Godfray, H.C.J. *et al.*, (2010). Food security: the challenge of feeding 9 billion people. *Science* **327,** 812-818 [DOI: 10.1126/science.1185383].

Godfray, H.C. J. and Garnet, T (2014). . Food security and sustainable intensification,

Phil. Trans. R. Soc. B 369: 20120273. http://dx.doi.org/10.1098/rstb.2012.0273

Government Office for Science London (2010), *Technology and innovation futures: UK growth opportunities for the 2020s,*

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/288564/10-1252-technology-and-innovation-futures.pdf

Government Office for Science London (2011). Foresight. The Future of Food and Farming. Final Project Report.

Government Office for Science London (2012), *Technology and innovation futures: UK growth opportunities for the 2020s,*

https://www.gov.uk/government/publications/technology-and-innovation-futures-uk-growth-opportunities-for-the-2020s

Hume, D.A., *et al.*, (2011), The future of animal production: improving productivity and sustainability. *Journal of Agricultural Science*, 149, 9–16.

Kirakosyan, P.B and Kaufman, P (editors) (2009). **Recent Advances in Plant Biotechnology,** Springer, Dordrecht, Heidelberg, London, New York.

Loos, J. *et al.*, (2014), Putting meaning back into "sustainable intensification. *Front Ecol Environ;* doi: 10. 1890/130157.

Pelletier, N. et al., (2011). Energy intensity of agriculture and food systems, *Annu. Rev. Environ. Resou*r. 36: 223-46.

Policy Horizons Canada (2012), *Building Resilience in the Transition to a Digital Economy and a Networked Society,*

http://www.horizons.gc.ca/sites/default/files/Publication-alt-format/metascan-en_interactive_1.pdf

Policy Horizons Canada (2013), *Emerging technologies*

http://www.horizons.gc.ca/eng/content/metascan-3-emerging-technologies-0

RISE Foundation (n.d.), *The sustainable intensification of European agriculture,*

http://www.risefoundation.eu/images/pdf/si%202014_%20full%20report.pdf

Sekhon, B.S. (2010). Nanotechnology in agri-food production: an overview. Nanotechnology, Science and Applications 7 31–53.

Sorrentino, A. *et al.*, *(*2007). Potential perspectives of bio-nanocomposites for food packaging applications. *Trends in Food Science & Technology, 18, 84-95.*

STOA (2009), *Nanotechnology in the food sector*, http://www.europarl.europa.eu/RegData/etudes/etudes/join/2009/424755/IPOL-JOIN_ET(2009)424755_EN.pdf

STOA project (2013a), *Technology options for feeding 10 billion people Synthesis report. Options for sustainable food and agriculture in the EU*,

http://www.europarl.europa.eu/RegData/etudes/etudes/join/2013/513539/IPOL-JOIN_ET(2013)513539_EN.pdf

STOA Project (2013b), *Technology options for feeding 10 billion people: Options for sustainable food processing, State of the art report.*

http://www.europarl.europa.eu/RegData/etudes/etudes/join/2013/513533/IPOL-JOIN_ET(2013)513533_EN.pdf

Teagasc (2008), *Towards 2030: Teagasc's role in transforming Ireland's agri-food sector and the wider bioeconomy*,

(http://www.teagasc.ie/publications/view_publication.aspx?PublicationID=285

Teagasc (2009), Agricultural biotechnology. *Food Harvest 2020 Background Paper*,

http://www.agriculture.gov.ie/agri-foodindustry/foodharvest2020/backgroundpapers/

The Royal Society (2009), *Reaping the benefits: science and the sustainable intensification of global agriculture*,

https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/4294967719.pdf

Thornton, P K (2010), Livestock production: recent trends, future prospects. *Phil. Trans. R. Soc. B.* 365, 2853-2867.

UNSDN . (2013). *Solutions for sustainable agriculture and food systems. Technical Report for the Post-2015 Development Agenda*,

http://unsdsn.org/wp-content/uploads/2014/02/130919-TG07-Agriculture-Report-WEB.pdf

US Grains Council (2011), *Food 2040: The future of food and agriculture in East Asia*,

http://www.grains.org/sites/default/files/pdfs/US-Grains-Council-Food-2040-Report-FINAL.pdf

Willets, D. (2013), **Eight Great Technologies**, Policy Exchange, London.