Destination 2025: Focus on the Future of the Food Industry

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A collaboration between
The BioBusiness Alliance of Minnesota
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Destination 2025

Focus on the Future of the Food Industry

Table of contents

Foreword

Deloitte Consulting LLP and The BioBusiness Alliance of Minnesota (BBAM) present this white paper on the future of the food industry. "Destination 2025: Focus on the Future of the Food Industry" is one of six industry papers that explore the future of six markets of the global biosciences industry. The other five markets include: Biologics and Biopharmaceuticals; Medical Devices; Animal Health; Renewable Energy; and Renewable Materials. These papers are also available on our websites www.biobusinessalliance.org and www.deloitte.com/us/d2025.

These six papers have been developed through a collaborative effort between Deloitte Consulting LLP and BBAM over the past year. This paper aims to inform decision makers in academia, government, and industry of a range of potential opportunities likely to emerge in the food industry, and to identify technologies, products, and knowledge clusters critical to taking advantage of these opportunities.

One specific application is to assist decision makers in Minnesota to understand the trajectory of the six life science markets over the coming decades, and then identify knowledge clusters to develop Minnesota's competitiveness. Based on this exploration of the future presented in this paper, decision makers in the state of Minnesota can start to develop a vision for each of the six markets, and given the convergence across the markets, develop a consolidated roadmap for the regional industry. Under the project Destination 2025, this application for each of the six markets has been executed to develop six vision papers and a roadmap for the state of Minnesota. The vision papers include recommendations for policy, education, and infrastructure to develop each of the six markets. The roadmap presents a consolidated set of recommendations for the Minnesota bioscience community. More than 600 leaders in academia, government, and industry from Minnesota have participated in the Destination 2025 project by developing the initial Strawman document, responding to online surveys, and participating in stakeholder meetings and expert validation sessions. These leaders have been identified in the Appendix. These documents are available to Minnesota stakeholders upon request.

Another application is for decision makers at the national, state, or local level to develop regional plans to accelerate economic activity, job creation, investments, and tax revenue.

At a more specific level, individual entities, in academia or industry, can develop strategies to improve their competitiveness by applying their entity-specific constraints to a range of opportunities emerging in the future.

The findings of this paper are a starting point for more flexible and informed strategic decision making.

Please feel free to contact us with your comments, queries, and suggestions.

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Executive summary

This paper aims to inform decision makers in academia, government, and industry of a range of potential opportunities likely to emerge in the food industry, and to identify technologies, products, and knowledge clusters critical to taking advantage of these opportunities.

We have identified potential growth opportunities in the food industry based on a broad view of emerging and future industry trends and technologies. The technology and product opportunities are matched against a range of future scenarios. The result is a portfolio of technologies, products, and knowledge clusters relevant for those scenarios, which can be a starting point for discussion about opportunities for the regional industry. Decision makers can begin with those opportunities to develop a vision for the region. Similarly, individual entities can themselves formulate strategies specific to their needs to manage the uncertain future.

1.0 Emerging and future trends

The following trends have been identified as those expected to influence the industry in the next 20 years.

Significant demographic and economic developments are increasing the demand for food. Population growth, increasing life expectancy, and economic growth are expanding the demand for food products. Economic growth in emerging economies and global convergence in food consumption are expanding demand for animal protein, dairy products, and processed foods. There is also increased demand for more healthful and specialized food products. There is an increasing reemphasis on economically priced, safe, quality food.

There is increasing emphasis on health and wellness derived from food. Demand for health and wellness from food is being driven by demographic and cultural factors: greater emphasis on healthy living in industrialized societies; the graying of the population in the developed world and its keen interest in health; and the increasing prevalence of illness and disease associated with high-fat and high-cholesterol foods in emerging and industrialized economies. Innovation in food products has built on these trends to develop the growing market for functional or health-enhancing foods. Matching specific foods or food choices with an individual's specific health needs is the future of the nutrition practice and food industry.

Increasing demand for food requires productivity improvements to leverage constant or declining inputs. Developed and developing agricultural systems are required to improve agricultural yields to meet growing demand for food. Genetic modification is a leading strategy for increasing agricultural yields, although many are concerned about its risks. Proliferation of integrated plant nutrient systems can improve plant nutrition and soil fertility and improve the productivity and sustainability of food production.

Resource constraints and degradation present a challenge to increase food production. Long-term water availability and reliability is at risk in many parts of the world. Water management infrastructure, improvements in the efficiency of irrigation systems, on-farm water management practices, and water efficiency in plants can improve water availability and efficiency. Increasing focus on soil management to improve water retention can be expected. The status of the world's fish populations and the health of its oceans are at risk. More cautious and controlled management of world fisheries is required.

Climate change poses significant risk to agriculture systems and food production. Water availability is expected to be highly sensitive to climate change. The enduring changes in climate, water supply, and soil moisture could adversely affect crop production in certain parts of the world. Climate change can significantly increase production risk and rural vulnerability, particularly in regions that already suffer from chronic soil and water resource scarcity or high exposure to climatic extremes, such as droughts and flooding. The agricultural sector's ability to adapt depends on changes in technology and demand for food, coupled with management of water availability, soil quality, and crop selection.

Managing climate change and environmental sustainability of food production and processing can be catalysts for modifying consumer and producer behavior and improving food production practices. Increasing concerns about the carbon footprint of food products is likely to spur changes in product labeling, certification of sustainable practices, and, if pursued seriously, significant changes in food production technology.

Increasing globalization of processed foods is expected to continue. Economic and demographic changes are creating higher trade volumes for processed food products. Large multinational corporations are expected to flourish in this space. However, large multinational retailers may also encourage local food manufacturing from domestically produced raw products. Demand for food scientists and technicians is expected to increase as a result.

Increasing globalization is also expected to elevate concerns and risks associated with the food supply chain. There may be increasing concerns about food safety and nationalistic concerns about food security and independence. Risks of epidemics associated with increased trade in animal and animal products need to be monitored. The food supply chain may also be increasingly vulnerable to man-made calamities and exogenous shocks.

Governments may respond with a range of actions to address concerns about food products. Governments may regulate food products more closely to respond to concerns. The regulations could affect food safety, ethics of biotechnology and nanotechnology, international trade, food labeling, and environmental sustainability. Governments may impose technical barriers to trade and country-of-origin labeling requirements.

Managing high energy and commodity prices is increasingly important for food production. The strengthening of linkages between agricultural commodities and between agricultural commodities and energy markets, development of biofuels, reduction in food stock levels, increasing frequency and magnitude of extreme weather, and higher demand for food commodities have contributed to the price increases for food commodities and products. High energy prices affect agriculture where inputs (fertilizer, mechanization at the farm) are energy intensive. On-farm energy management has huge potential for improving the environment, lowering farm production costs, and decreasing reliance on foreign energy supplies.

Managing the impact of biofuels requires policy development across multiple stakeholders and technological innovation. The extent of competition between crops for biofuels with food production remains a significant question that needs to be addressed by a broad range of stakeholders. Advances in biotechnology can mitigate the impact of biofuels on food production. The developments may decrease or increase the pressure on land and water resources as the first generation of biofuels gives way to the second generation.

Workforce constraints are likely to affect food production and processing. In the United States, the limited supply of food scientists and technicians is likely to affect the development of the food processing industry. In emerging economies, increasing trade and local food processing are also expected to increase demand for food scientists and technicians. Graying of the U.S. farm workforce requires additional workers. Immigrant workers are an alternative, but resolution of certain immigration policies is required to suitably address the labor supply problem.

2.0 Emerging and future technologies and products

Five groups of technologies are expected to drive the food industry:

- Technologies that improve the productivity of agricultural systems and animal production
- Technologies and practices that improve the sustainable use of inputs
- Technologies that improve the health and wellness qualities of food
- Food processing technologies
- Food safety and supply chain management technologies

Technologies that boost productivity and quality

Sustainable breeding through genomics: Current research is providing the fundamental knowledge of the genomics and epigenetics of animal health, food safety, and food-quality traits of livestock species, as well as new strategies to deliver such technologies.

Genome sequence identification in beef animals: An integrated genetic map has been developed to help researchers assemble and annotate the bovine genome sequence. These accomplishments greatly accelerate the discovery of DNA markers suitable for marker-assisted selection (MAS) and fine mapping of genes for economically important traits in cattle.

Disease resistance and managing attributes through genomics: The leading-edge biotechnologies to influence the future of food and animal production are expected to be genomics and functional genomics, bioinformatics, genetic modification and transgenesis, gene expression, DNA microarrays, marker-assisted breeding, and quantitative trait loci.

Molecular marker technology in plant breeding: Molecular markers are a powerful tool that can pinpoint genes and manipulate them directly to create new, improved varieties.

Intragenic crop improvement: The intragenic approach to genetic engineering can improve existing varieties by eliminating undesirable features and activating dormant traits.

Clonal seed production: Clonal seed production, or apomixis, promises to revolutionize plant breeding by providing a system for improving crops that allows any desired variety, including hybrids, to breed with uniformity.

Biological containment of genetically modified plants: Biological containment systems are important to reduce the potential risk of any unintentional release of genetically modified organisms into the environment.

Functional transgenic crop-based foods: Transgenic approaches can complement ongoing breeding efforts and provide the urgently needed biofortified crops to feed the burgeoning world population with functional and nutritious food.

High-throughput approaches to optimize nutritional value: Novel high-throughput genotyping technologies are expected to play a key role in developing large-scale analyses of plant genotypes to identify defined differences, or DNA polymorphisms, in their genetic structure.

Combinatorial biosynthesis to generate new natural products: Combinatorial biosynthesis is a tool that can create natural, rare and expensive products. The basic concept involves combining metabolic pathways in different organisms on a genetic level.

Technologies and practices that improve the sustainable use of inputs

Renewable soil fertility replenishment technologies: Low soil fertility is one of the most important biophysical constraints to increasing agricultural productivity in sub-Saharan Africa. In the foreseeable future, discussions on the development of sub-Saharan Africa will increasingly focus on the need to enhance food production while maintaining the agricultural resource base and the resilience of the agroecosystem. Renewable Soil Fertility Replenishment (RSFR) technologies are likely to remain a key part of that discussion.

Increasing water efficiency of crops: Recent research may lead to increased plant water use efficiencies through genetically manipulating stomatal density.

Farming using salt water: Seawater can be used in four basic ways in agriculture. Desalinization extracts salt from the water, but remains generally too expensive for widespread use in agriculture. In farming areas close to the coastline, deep and very cold seawater can be used to induce moisture from the local atmosphere. Seawater greenhouses can use sunlight to vaporize or re-precipitate seawater. Finally, seawater can be directly used for irrigation of halophyte, or salt-tolerating, plant stock. The outlook for genomic-derived halophyte enhancements appears to be quite favorable.

Novel water purification technologies: Next-generation purification systems include novel methods to disinfect water without intensive use of chemicals or the production of toxic byproducts. These techniques sense, transform, and remove low-concentration contaminants even in high backgrounds of potable constituents — using, for instance, photons and engineered nanostructures or microorganism-based water purification technologies.

Technologies that improve the health and wellness attributes of food

Food as a vehicle for drug or biologic delivery: Particulate drug delivery systems have become widely used in clinical and experimental therapeutics in a range of applications targeting different disease states. Considering many consumers prefer food as a vehicle for drug delivery, it is likely that the technology will become widespread in the future.

Microencapsulation in food: Microencapsulation has been used successfully for drug delivery for several decades, but its use in food is still quite new and is composed of a limited array of workable Generally Recognized as Safe (GRAS) encapsulating agents and technologies.

Molecular docking to predict enzyme functioning: Molecular docking in enzymology has huge potential for food technology as a way to deliver drugs or biologics.

Nutrigenomics to customize diets: Research findings on the interrelationship between nutrition and the human genome are creating commercial applications both for producing food and for preventing diet-related diseases through, for instance, diagnostic tools.

Food processing technologies

Nanotechnology for food applications: Nanotechnology allows designers to alter the structure of packaging materials on the molecular scale to give the materials desired properties.

Green chemistry applications in packaging: Novel and advanced polymeric materials based on green chemistry are being developed to enhance food packaging. Work in this area uses conventional polymer science methods, as well as newer technologies, including biopolymers, nanotechnology, and nanocomposites, to create active, intelligent packaging.

Microbial transformation for producing natural flavors: Microbial transformation, which alters flavors by the addition of specific microorganisms, has emerged as an important approach for producing natural flavors in high quantities.

Food safety and supply chain management technologies

Information systems to manage food supply chains: The dynamic and longer food supply chains need more research attention. The future in information systems to monitor food supply chains is expected to include the wide acceptance of advanced, high-speed information and communication technologies through partnering with companies or outsourcing services.

Non-thermal food processing: Several non-thermal processing methods and technologies are currently available or in development to deactivate microorganisms, extend microbiological shelf life in foods, and identify packaging interactions that might result in unsafe food. Those techniques include ultra-high-pressure techniques, ionizing radiation, such as pulsed x-ray, ultrasound, pulsed light and pulsed electric fields, high-voltage arc discharge, magnetic fields, dense phase carbon dioxide, and hurdle technologies.

Real-time sensing of pathogens: The need for real-time monitoring in the modern, highly automated food processing environment has stimulated research into rapid microbiological testing that can detect microbial spoilage in meats within seconds as opposed to hours. This can be developed based on advances in analytical instrumentation, progress in miniaturization of those instruments, the increasing speed of computer processing, and better tools for more complex data analysis.

Biosensors for rapid detection of viruses: New biosensor technologies are being developed to identify pathogens in clinical, food, and environmental samples.

Technologies to screen for multiple chemical contaminants: Rapid and efficient transcriptomics, proteomics, and biosensor-based technologies are being developed and are expected to improve the task of screening for chemical contaminants.

3.0 Exploring possible futures and identifying opportunities

The first two sections of this paper give a broad view of the trends, technologies, and products that are expected to affect the food industry. Section 3 provides a framework through which opportunities can be identified and pursued. By laying out a range of possible future scenarios, and matching the relevant technologies and products to each, we have identified a portfolio of technologies and products relevant across a range of scenarios.

Product and technology portfolios

The following emerging technologies and products are expected to significantly shape the industry.

Table: Product and technology portfolios

		Scenarios								
Technologies	Products	Death by association	Cows don't come home	The world of omics, ology et al.	"That's hot!"	Maslow vs. Malthus	Boom	Slippage	One world	Consumer's world
Molecular biology / microbiology										
Protein manipulation at the molecular level	Molecular docking proteins with improved hit identification and maximized lead optimization to enhance nutrient delivery of drug/bio treatments through food			✓		✓	✓		✓	
Protein sensing and monitoring	Microbiology sensing products to detect spoilage in agriculture and animal products (priority is for muscle foods)			✓		✓			✓	
Genetic engineering										
Genome sequencing and mapping	Integrated genetic map with over 17,000 markers from other linkage and hybrid maps from around the world			✓	✓	✓	✓			
Genome sequencing and mapping	Generated and annotated cDNA sequences for improving animal feed efficiency and environmental sustainability			✓	✓	✓				
Genome sequencing and mapping	Bovine genome tools to develop gene selection methods			✓	✓	✓				
Proteomic combinations for better health	Transgenic animals to supply pharmaceutical proteins and transplantable organs for humans			✓		✓				
Proteomic combinations for better health	Metabolic pathway combinations to produce rare and expensive natural products, making them more affordable to produce			✓	✓	✓		✓		
Proteomic combinations for better health	Functional enhancement by increasing genetic properties of foods (e.g., high-antioxidant and low-allergenicity content)			✓		✓				
Proteomic combinations for better health	Efficient combination of proteins to produce foods more affordably				✓	✓		✓		
High-throughput biology	Clonal seed production of crops so that any hybrid varieties breed true and shorten time to market				✓	✓	✓		✓	✓
Environmental sustainability										
Bioengineering for improved functionality	Food crops with increased efficiency in transpiration and photosynthesis (bio-water)			✓	✓	✓	✓		✓	✓
Bioengineering for improved functionality	Food crops with Renewable Soil Fertility Replenishment (RSFR) properties			✓	✓	✓	✓			✓
Bioengineering for improved functionality	Inorganic fertilizers			✓	✓					
New planting and production techniques with sustainable resources and materials	Use of halophyte plants to provide seawater irrigation and use of saline aquifers; genomics can play a role in enhancing halophyte water desalination efficiency			✓	✓				✓	✓
New planting and production techniques with sustainable resources and materials	Local crop generation to meet local demand offers the greatest use of next generation technologies to sustain the environment			✓	✓				✓	✓
Nutrigenomics										
Proteomic combinations for better health	Customization of foods based on nutrition/dietary needs				✓		✓			✓
Proteomic combinations for better health	Customization of foods to help treat chronic, sub-acute, and acute diseases/infections (e.g. cancers, type-2 diabetes, Chrons disease, high blood pressure, flu, and rashes)			✓	✓		✓			✓
Food supply chain information systems										
Bioinformatics systems and solutions	Bioinformatics for DNA matrix arrays containing annotated sequences and linkage/hybrid maps and other genetic makeup data	✓	✓	✓	✓	✓				
Supply chain technology infrastructure and monitoring tools	ICTs - Information Communication Technologies that link the field to the check out lane for food and animal products			✓		✓	✓			
Supply chain technology infrastructure and monitoring tools	Virtual Enterprise Networks - connections between industry, academic, and government research resources			✓	✓		✓		✓	
Supply chain technology infrastructure and monitoring tools	Collaborative design technologies for use with food and animal product manufacturers, food packaging manufacturers, and distributors			✓	✓	✓		✓	✓	
Supply chain technology infrastructure and monitoring tools	Supply chain integration with regulatory agencies to accelerate containment of recalled food and animal products	✓	✓		✓		✓		✓	

Table: Product and technology portfolios (continued)

Technologies	Products	Scenarios								
		Death by association	Cows don't come home	The world of omics, ology et al.	"That's hot!"	Maslow vs. Malthus	Boom	Slippage	One world	Consumer's world
Food safety / biological containment										
Food safety systems, technology, and monitoring tools	Biosensors integration within the food supply chain monitoring for changes to safety of food and animal resources, products, and sharing of food safety leading practices	✓	✓	✓	✓		✓		✓	
Food safety systems, technology, and monitoring tools	Biological containment systems for isolating contaminated food crops and animals and to prevent crossbreeding/pollination of genetically modified food crops and animals	✓	✓	✓	✓	✓	✓		✓	✓
Food safety systems, technology, and monitoring tools	Rapid and efficient transcriptomics, proteomics, and biosensor-based technologies are in development for detecting a wide variety of contaminants	✓	✓	✓						
Nanotechnology										
Packaging utilizing nanotech and materials science	Multi-functional packaging (keeps food cold without freezing or packaging adhering to product)			✓	✓	✓	✓		✓	
Packaging utilizing nanotech and materials science	Anti-microbial packaging designed to seek and destroy food contaminants and microorganisms			✓	✓	✓	✓		✓	
Food protection additives using nanotech and materials science	Nanosensor materials that detect toxins, chemicals, and pathogens and alert consumer to their contents prior to exposure			✓	✓	✓				
Food protection additives using nanotech and materials science	Nanocoatings designed to serve as repellents to dirt, fungi, and other unwanted product contaminants			✓						
Packaging utilizing nanotech and materials science	Nanotubes, nanowheels, nanofibers can be used to ensure efficient breakdown of packaging material for recycling/recombination			✓	✓					
Green chemistry										
Packaging utilizing nanotech and materials science	Reduction or elimination of hazardous substances using advanced polymeric materials in food packaging; biopolymers, nanotechnology and nanocomposites, and active and intelligent packaging properties are all potential green chemistry packaging materials			✓	✓					
Packaging utilizing nanotech and materials science	Biological-based materials with nanotechnology would provide products for flexible and rigid packaging sectors				✓		✓			
Non-thermal food processing										
Sterilization from radiation, electricity, magnetic, or carbon dioxide-based food processing technologies	Ionizing radiation from pulsed x -rays, pulsed light and electric fields, high-voltage arc discharge, magnetic fields, dense phase carbon dioxide (CO_2)	✓	✓	✓	✓	✓	✓			
Sterilization from nanotech and materials science food processing technologies	Hurdle technologies that include new packaging materials			✓						
Resource purification										
Purification technologies improving availability of sustainable resources with minimal by-products	Disinfection of water to remove low-concentration contaminants and provide ability to re-use waste water with minimal toxic by-products; use of photons and engineered nanostructures, and microorganism-based technologies				✓				✓	✓
Drug / biological treatment delivery										
Food products capable of drug/biological treatment delivery	Foods designed for drug/biologic delivery	✓	✓							
Food products capable of drug/biological treatment delivery	Snacks to be taken over several days to release the correct drug dosage	✓	✓							
Basic ingredients and additives used to deliver drug and biological treatments	Basic ingredients and food additives designed to be cooked with/combined with other foods to release the correct drug dosage over several days	✓	✓						✓	
High nutrition and environmentally sustainable food products										
Proteomic combinations for better health	Organic food and animal products from local sources that contain nutritional elements based on specific dietary needs						✓			✓
Proteomic combinations for better health	Genetically modified food and animal products that contain high-nutrient levels from high-efficiency crop yields and livestock			✓	✓	✓		✓	✓	

Summary of technologies and knowledge clusters

By further matching these technologies and products with the knowledge clusters necessary for their development, we can identify areas of focus and potential investment. The following knowledge clusters are expected to significantly shape the industry.

Table: Summary of technologies and knowledge clusters

Technologies	Products	Catalysis	Synthesis	Bioengineering	Clinical capabilities	Systems biology	Genomics and proteomics	Nanotechnology	Materials science	Imaging/ navigation	Computer science	Data management and analysis
Proteomics												
Protein manipulation at the molecular level	Molecular docking proteins with improved hit identification and maximized lead optimization to enhance nutrient delivery of drug/bio treatments through food	✓	✓	✓	✓		✓	✓			✓	✓
Protein sensing and monitoring	Microbiology sensing products to detect spoilage in agriculture and animal products (priority is for muscle foods)						✓	✓			✓	✓
Genetic engineering												
Genome sequencing and mapping	Integrated genetic map with over 17,000 markers from other linkage and hybrid maps from around the world					✓	✓				✓	✓
Genome sequencing and mapping	Generated and annotated cDNA sequences for improving animal feed efficiency and environmental sustainability			✓	✓	✓	✓				✓	✓
Genome sequencing and mapping	Bovine genome tools to develop gene selection methods			✓		✓	✓				✓	✓
Proteomic combinations for better health	Transgenic animals to supply pharmaceutical proteins and transplantable organs for humans	✓	✓	✓	✓	✓	✓				✓	✓
Proteomic combinations for better health	Metabolic pathway combinations to produce rare and expensive natural products, making them more affordable to produce	✓	✓			✓	✓					
Proteomic combinations for better health	Functional enhancement by increasing genetic properties of foods (e.g., high-antioxidant and low-allergenicity content)	✓	✓	✓			✓	✓				
Proteomic combinations for better health	Efficient combination of proteins to produce foods more affordably	✓	✓	✓			✓	✓				
High-throughput biology	Clonal seed production of crops so that any hybrid variety breeds true; shortens time to market			✓		✓	✓				✓	✓
Environmental sustainability												
Bioengineering for improved functionality	Food crops with increased efficiency in transpiration and photosynthesis (bio-water)	✓	✓	✓		✓	✓					
Bioengineering for improved functionality	Food crops with RSFR properties			✓		✓	✓					
Bioengineering for improved functionality	Inorganic fertilizers	✓		✓				✓	✓			
New planting and production techniques with sustainable resources and materials	Use of halophyte plants to provide seawater irrigation and use of saline aquifers; genomics can play a role in enhancing halophyte water desalination efficiency	✓	✓	✓		✓	✓	✓	✓			
New planting and production techniques with sustainable resources and materials	Local crop generation to meet local demand offers the greatest use of next-generation technologies to sustain the environment			✓		✓	✓					
Nutrigenomics												
Proteomic combinations for better health	Customization of foods based on nutrition/dietary needs	✓	✓	✓	✓	✓	✓	✓			✓	✓
Proteomic combinations for better health	Customization of foods to help treat chronic, sub-acute, and acute diseases/infections (e.g. cancers, type-2 diabetes, Chrons disease, high blood pressure, flu, and rashes)	✓	✓	✓	✓	✓	✓	✓			✓	✓
Food supply chain information systems												
Bioinformatics systems and solutions	Bioinformatics for DNA matrix arrays containing annotated sequences and linkage/hybrid maps and other genetic makeup data			✓	✓	✓	✓				✓	✓
Supply chain technology infrastructure and monitoring tools	ICTs — Information Communication Technologies that link the field to the check out lane for food and animal products							✓	✓		✓	✓
Supply chain technology infrastructure and monitoring tools	Virtual Enterprise Networks - connections between industry, academic, and government research resources							✓	✓		✓	✓
Supply chain technology infrastructure and monitoring tools	Collaborative design technologies for use with food and animal product manufacturers, food packaging manufacturers, and distributors							✓			✓	✓

Table: Summary of technologies and knowledge clusters (continued)

Technologies	Products	Catalysis	Synthesis	Bioengineering	Clinical capabilities	Systems biology	Genomics and proteomics	Nanotechnology	Materials science	Imaging/ navigation	Computer science	Data management and analysis
Supply chain technology infrastructure and monitoring tools	Supply chain integration with regulatory agencies to accelerate containment of recalled food and animal products							✓		✓	✓	✓
Food safety / biological containment												
Food safety systems, technology, and monitoring tools	Biosensors integration within the food supply chain monitoring for changes to safety of food and animal resources, products, and sharing of food safety leading practices	✓	✓	✓		✓	✓	✓			✓	✓
Food safety systems, technology, and monitoring tools	Biological containment systems for isolating contaminated food crops and animals and to prevent crossbreeding/pollination of genetically modified food crops and animals						✓	✓	✓		✓	✓
Food safety systems, technology, and monitoring tools	Rapid and efficient transcriptomics, proteomics, and biosensor-based technologies are in development for detecting a wide variety of contaminants	✓	✓	✓		✓	✓	✓			✓	✓
Nanotechnology												
Packaging utilizing nanotech and materials science	Multi-functional packaging (keeps food cold without freezing or packaging adhering to product)	✓	✓				✓	✓	✓			
Packaging utilizing nanotech and materials science	Anti-microbial packaging designed to seek and destroy food contaminants and microorganisms	✓	✓				✓	✓	✓		✓	✓
Food protection additives using nanotech and materials science	Nanosensor materials that detect toxins, chemicals, and pathogens and alert consumer to their contents prior to exposure	✓	✓	✓			✓	✓	✓	✓	✓	✓
Food protection additives using nanotech and materials science	Nanocoatings designed to serve as repellents to dirt, fungi, and other unwanted product contaminants							✓	✓		✓	✓
Packaging utilizing nanotech and materials science	Nanotubes, nanowheels, nanofibers can be used to ensure efficient breakdown of packaging material for recycling/recombination							✓	✓		✓	✓
Green chemistry												
Packaging utilizing nanotech and materials science	Reduction or elimination of hazardous substances using advanced polymeric materials in food packaging; biopolymers, nanotechnology and nanocomposites, and active and intelligent packaging properties are all potential green chemistry packaging materials	✓	✓	✓			✓	✓	✓		✓	✓
Packaging utilizing nanotech and materials science	Biological-based materials with nanotechnology would provide products for flexible and rigid packaging sectors	✓	✓				✓	✓	✓			
Non-thermal food processing												
Sterilization from radiation, electricity, magnetic, or carbon dioxide-based food processing technologies	Ionizing radiation from pulsed x-rays, pulsed light and electric fields, high-voltage arc discharge, magnetic fields, dense phase carbon dioxide (CO_2)						✓	✓		✓	✓	✓
Sterilization from nanotech and materials science food processing technologies	Hurdle technologies that include new packaging materials	✓	✓	✓			✓	✓			✓	✓
Resource purification												
Purification technologies improving availability of sustainable resources with minimal by-products	Disinfection of water to remove low-concentration contaminants and provide ability to re-use waste water with minimal toxic by-products; use of photons and engineered nanostructures, and microorganism-based technologies	✓	✓					✓	✓			
Drug / biological treatment delivery												
Food products capable of drug/biological treatment delivery	Foods designed for drug/biologic delivery	✓	✓	✓	✓		✓	✓			✓	
Food products capable of drug/biological treatment delivery	Snacks to be taken over several days to release the correct drug dosage	✓	✓	✓	✓		✓	✓			✓	
Basic ingredients and additives used to deliver drug and biological treatments	Basic ingredients and food additives designed to be cooked with/ combined with other foods to release the correct drug dosage over several days	✓	✓	✓	✓		✓	✓			✓	
High nutrition and environmentally sustainable food products												
Proteomic combinations for better health	Organic food and animal products from local sources that contain nutritional elements based on specific dietary needs					✓	✓				✓	✓
Proteomic combinations for better health	Genetically modified food and animal products that contain high-nutrient levels from high-efficiency crop yields and livestock		✓	✓		✓	✓	✓			✓	✓

4.0 Next steps

The research, scenarios, and findings in these papers were developed for a very specific purpose: to assist BBAM define a set of core and contingent strategies for Destination 2025. From this analysis of technologies, products, and knowledge clusters, and the opportunities identified in the broad exploration of the future, two applications are possible. First, individual entities can formulate strategies based on their resource constraints, investment and risk appetite, and market position.

Second, stakeholders in a regional industry can use the findings of this paper to develop specific entities or the collective regional industry. Decision makers in academia can use the portfolio of technologies and products identified to analyze their research portfolio and reconfigure it. They can also build knowledge clusters required to develop their academic and research programs.

Decision makers in industry can use the findings of this paper to identify opportunities presented by emerging technologies and market trends. They can develop technologies and products by acquiring relevant expertise or conducting in-house research. Decision makers in industry can also develop specific strategies by applying their resource constraints to a selected range of opportunities identified in this paper.

Decision makers in government can use the opportunities identified in this paper to develop the competitiveness of the regional industry and with it attract regional human capital, investments, and new businesses. Government can develop policies and invest in education and infrastructure to improve the competitiveness of the regional industry.

Collectively, the findings of this paper can be used to develop a vision for the future of a regional industry with specific recommendations for policy, education, and infrastructure development.

The interpretation of the findings and potential next steps identified in this paper will vary according to the reader's current position, objectives, and constraints. For Minnesota stakeholders, use of these materials should be undertaken with the guidance of BBAM in their role to facilitate the implementation of Destination 2025 strategies in the state of Minnesota. BBAM and Deloitte Consulting LLP are not responsible for any actions taken by anyone based on the content of this report.

Introduction

This paper explores the future of the global food industry. The goal is to inform decision makers in academia, government, and industry of a range of potential opportunities likely to emerge in the food industry and to identify technologies, products, and knowledge clusters critical to taking advantage of these opportunities.

We have identified potential growth opportunities in the food industry based on a broad view of emerging and future industry trends and technologies. The technology and product opportunities were then matched against a range of future scenarios. The result is a portfolio of technologies, products, and knowledge clusters, which can be a starting point for discussion about opportunities for a regional industry.

We begin by defining the food market. We then investigate emerging and future market, cultural and demographic, environmental, economic and trade, and workforce trends that are likely to influence the industry.

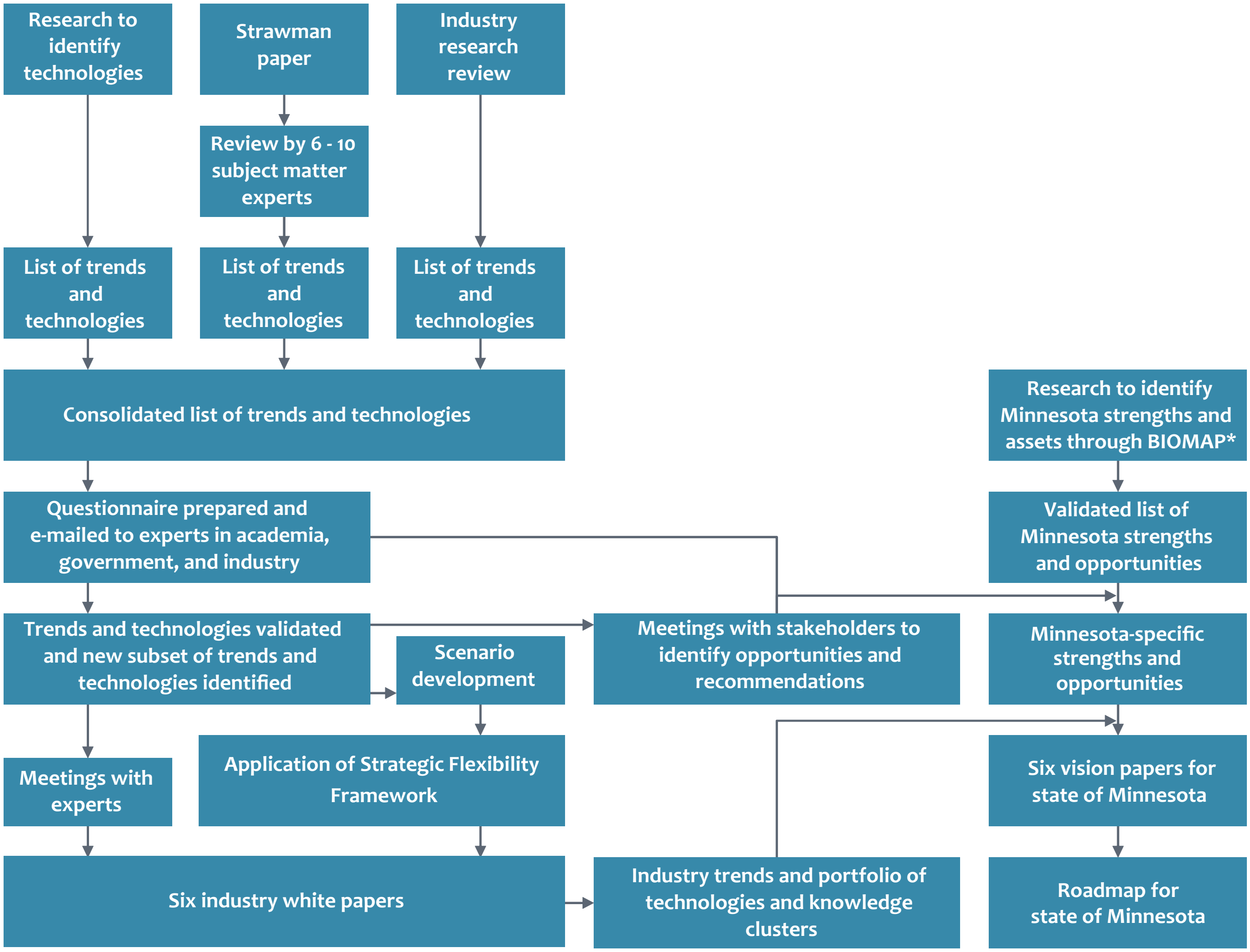
We then explore emerging and future technologies and products. While it is impossible to investigate an exhaustive list, or to establish with certainty how these technologies and products will impact the industry, generating a range of opportunities provides options for decision makers to consider. For example, leaders in industry can use the information to configure or reconfigure their product or research and development portfolios. Leaders in academia may use the information to create research and development initiatives or maintain academic and research programs. Government leaders may use the information to determine investments in education systems or to anticipate types of policies, standards, and regulations to improve the safety of their constituents. Decision makers interested in developing a regional industry can use the identified opportunities as a starting point to develop a vision for their region.

Since it is impossible to predict the future with complete certainty, it is important to have a flexible framework for exploring a range of possible future scenarios. In such a framework, decision makers can see the flux of trends and technologies and can identify a range of technologies, products, and expertise likely to be important across these scenarios. Specific entities can develop strategies to cope with specific resource constraints, such as investment capacity, existing capabilities, and risk appetite. We define such a framework. We then modify the framework so that multiple stakeholders in academia, government, and industry can explore different scenarios and identify portfolio of products, technologies, and knowledge clusters.

From this analysis of technologies, products, and knowledge clusters, and the opportunities identified in the broad exploration of the future, two applications are possible. Decision makers in academia, government, and industry can match these opportunities with regional strengths to develop a vision for their regions. Similarly, individual entities can formulate strategies based on their constraints and objectives to manage the future.

Given the uncertainty associated with predicting the future, particularly in an exercise spanning two decades, we used a process that involved knowledge from diverse sources and participation of national and, as much as possible, international leaders from industry, academia, and government. The knowledge was validated at multiple levels by multiple stakeholders and experts. This process was applied to identify and validate both trends and technologies. The process is described in Figure 1 on the next page.

Figure 1: Destination 2025 process



*BIOMAP is an information database for the Minnesota biobusiness community: http://network.biobusinessalliance.org/

Market definition

Food is any substance, whether processed, semi-processed, or raw, that is intended for human consumption.[1] This includes drinks, chewing gum, and any substance that has been used in the manufacture, preparation, or treatment of "food"; but it does not include cosmetics, tobacco, or substances used only as drugs.

The scale and scope of the U.S. food industry is the biggest in the world. In 2006, it was a $1.4 trillion sector, accounting for 12.3 percent of gross domestic product (GDP) and 17 percent of the country's workforce — the second largest U.S. employer behind government.

Poultry

Poultry exports continue to grow worldwide. Total world poultry exports for 2007 were $3.2 billion (Table 1). China and the European Union (EU) are expected to be net broiler meat importers again in 2008 because of continued strong demand, higher domestic prices, and strengthening currencies. China is supplied mostly by the United States, whereas the EU imports poultry products from Brazil and Thailand.[2]

Animal husbandry (meat and dairy)

Uncertainty continues to plague dairy markets as fuel and feed costs fluctuate and weather factors disrupt expected production patterns. Yet amid high world prices, dairy product demand remained surprisingly robust. In 2007, total U.S. dairy exports were $2 billion, a four-fold increase from 2003. According to the U.S. Department of Agriculture (USDA), U.S. dairy exports have been expanding at a record-setting pace during the past four years (Table 2).[3] Although world growth for 2008 could drop because of fluctuating energy costs and the global credit crisis, GDP growth in the key East Asian markets remains likely to fuel continued growth in the dairy product market in the long run.

Demand for meat continues to grow worldwide, especially from developing countries. Table 3 illustrates recent growth of trade in meat. Global meat exports totaled $8.5 billion in 2007.

Table 1: Poultry exports (US $thousands)

	January - December					January - June		
	2003	2004	2005	2006	2007	2007	2008	% Change
World total	1,733,550	2,033,006	2,483,757	2,216,308	3,251,576	1,421,521	1,911,935	34.5
North America	394,285	509,899	586,025	579,169	679,593	348,714	359,635	3.1

Source: Department of Commerce, U.S. Census Bureau, Foreign Trade Statistics

Table 2: Dairy exports (US $thousands)

	January - December					January - June		
	2003	2004	2005	2006	2007	2007	2008	% Change
World total	527,009	922,911	1,039,137	1,219,554	2,033,394	806,102	1,528,260	89.6
North America	231,888	346,568	435,848	412,560	796,425	308,863	478,408	54.9

Source: United States Department of Agriculture, Department of Commerce, U.S. Census Bureau, Foreign Trade Statistics

1 Codex Alimentarius. http://www.codexalimentarius.net/web/index_en.jsp. Retrieved on September 3, 2008.

2 United States Department of Agriculture (2008) Livestock and Poultry: World Markets and Trade. Circular Series DL&P 1-08, Foreign Agricultural Service, United States Department of Agriculture, Washington, D.C.

3 United States Department of Agriculture (2008) Current World Production, Market and Trade Reports. *Feature Reports*, Foreign Agricultural Service, United States Department of Agriculture, Washington, D.C.

Table 3: World meat exports (US $thousands)

	January - December					January - June		
	2003	2004	2005	2006	2007	2007	2008	% Change
World								
Processed red meat	4,104,793	2,081,030	2,831,978	3,575,596	4,272,084	1,949,573	2,976,544	52.7
Poultry	1,733,550	2,033,006	2,483,757	2,216,308	3,251,576	1,421,521	1,911,935	34.5
Offal — Red meat	864,612	553,046	727,950	783,175	905,063	395,961	599,051	51.3
Preserved meat — Ham, bacon	59,567	61,499	64,959	74,260	59,282	31,725	27,373	-13.7
Other meats — Frog, rabbit, etc.	18,223	24,652	18,911	12,517	6,485	2,697	2,585	-4.2
Total	6,780,745	4,753,232	6,127,555	6,661,856	8,494,490	3,801,477	5,517,488	45.1
North America								
Processed red meat	1,105,441	902,750	1,239,076	1,711,914	1,806,649	840,510	1,063,113	26.5
Poultry	394,285	509,899	586,025	579,169	679,593	348,714	359,635	3.1
Offal — Red meat	384,906	396,218	499,785	556,581	621,996	274,533	354,986	29.3
Preserved meat — Ham, bacon, etc.	39,930	49,602	49,488	58,500	43,578	23,841	18,256	23.4
Other meats — Frog, rabbit, etc.	9,307	8,084	8,066	7,480	5,353	2,305	2,107	-8.6
Total	1,933,870	1,866,552	2,382,440	2,913,645	3,157,169	1,489,903	1,798,096	20.7

Source: US Department of Agriculture, Department of Commerce, U.S. Census Bureau, Foreign Trade Statistics

Food crops

Worldwide grain production was about 2.12 billion metric tons in 2007, as shown in Table 4. While much of the U.S. food crop is used domestically, a significant amount is exported. In 2007, the United States exported 49 percent of its food grains, 16 percent of feed grains, and more than 38 percent of oilseeds. During the previous two years, those percentages held steady for food-grain exports and decreased for feed-grain exports, while oilseed exports increased significantly. Because exports increased more than imports, net agricultural exports in 2006 contributed $5.7 billion to the overall U.S. economy, $2.1 billion more than in 2005.[4]

Table 4: Crop production (million metric tons)

	2006-07			2007-08		
	World	Foreign	U.S.	World	Foreign	U.S.
Wheat	596.3	547	49.3	610.5	554.3	56.2
Coarse grains	988.8	708.7	280.1	1076	724.9	351.1
Rice milled	420.2	413.9	6.2	429	422.7	6.3
Total grains	2,005.3	1,669.6	335.7	2,115.5	1,701.9	413.6
Oilseeds	403.3	306.7	96.6	387.2	307.2	80
Cotton	122	100.4	21.6	119.3	100.1	19.2

Source: USDA-ERS

Processed foods

Processed foods account for about three-fourths of total world food sales, amounting to $3.2 trillion, with more than 40 percent involving the food service sector.[5] In the retail sector, $531 billion of food sales are fresh products, while $1.7 trillion are processed foodstuffs — about $1.1 trillion of which is packaged food and $641 billion is beverages.[6] Although processed foods sales are a major component of global food markets, only 10 percent are traded products, representing around $320 billion. France led the world in processed food exports in 2006, with sales of $32.8 billion, or approximately 10 percent of the global processed food trade.[7]

Seafood

U.S. fish and seafood product exports were valued at more than $4.1 billion in 2007, an increase of 1 percent or $34 million compared to 2006. Exports increased in three of the five top markets, which account for 85 percent of U.S. fish and seafood product exports. U.S. exports to China were $537 million and increased more than any other market, rising 21 percent. Salmon exports increased more than any other fish or seafood product, rising 19 percent to $776 million from 2006 to 2007.[8]

4 Edmondson, W. (2008) U.S. Agricultural Trade Boosts Overall Economy. FAU-124. Economic Research Service, USDA

5 Regmi, A., and Gehlhar, M., eds. (2005) New Directions in Global Food Markets, *Agriculture Information Bulletin -794*, Economic Research Service/USDA

6 Gehlhar, M., and Regmi, A. (2005) Factors Shaping Global Food Markets. In: Anita Regmi and Mark Gehlhar, (editors) New Directions in Global Food Markets, AIB-794, Economic Research Service/USDA

7 Gauthier, R. (2007) France Still Offers Opportunities for U.S. Food and Agricultural Products Foreign Agricultural Service, United States Department of Agriculture, Washington, D.C.

8 United States Department of Agriculture (2008) World Markets and Trade: Fish and Seafood Products Foreign Agricultural Service/USDA Office of Global Analysis

Aquaculture

Although high growth rates may continue for some regions and species, the rate of growth for global aquaculture may have peaked. In 2004, aquaculture production was reported to be 45.5 million tons, with a value of $63.3 billion, or $70.3 billion if aquatic plants are included.[9] China accounted for nearly 70 percent of the worldwide production and more than half the global value of aquaculture production.

Functional foods and dietary supplements

The world market for functional foods and beverages is highly dynamic. However, confusing classification and terminology make it difficult to estimate the size of this sector. The global functional foods market has been valued at approximately $30 billion to $60 billion, depending on the definition. [10]

According to a 2007 survey, Japan is the world's largest market for these products at $11.7 billion.[11] The United States is second with around $10.5 billion, followed by the less-developed $7.5 billion "Big Four" European markets of the United Kingdom at $2.6 billion, Germany at $2.4 billion, France at $1.4 billion, and Italy at $1.2 billion. Demand for these products has grown in developing countries, such as Brazil, Peru, and Kenya, which are emerging as active exporters.[12]

The increased demand for functional foods within developing countries presents an opportunity to develop lucrative domestic markets. India, with its strong tradition of eating healthy foods, ranks among the top 10 consumers of functional foods, and its market size is expected to nearly double in the next five years.[13] In Brazil, the sector is relatively young, but it is growing rapidly, with sales projected to reach $1.9 billion by 2009. In China, the total functional foods market is approximately $6 billion per year, a number expected to double by 2010.[14] Probiotics are becoming an increasingly significant part of several industries, with an estimated value of $185 million in the food and beverage market, $1 billion in the dietary supplement market, and $9 billion in the animal feed market.[15]

With this overview of the industry, we now analyze the emerging and future trends and technologies that are expected to influence the industry.

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9 Food and Agriculture Organization (2007) The State of World Fisheries and Aquaculture 2006. FAO Fisheries and Aquaculture Department.

10 Kotilainen, L., Rajalahti, R., Ragasa, C., and Pehu, E.(2006) Health Enhancing Foods Opportunities for Strengthening the Sector in Developing Countries. Agriculture and Rural Development. *Discussion Paper 30*. The World Bank.

11 Subirade, M. (2007) Report on Functional Foods. Food Quality and Standards Service (AGNS) Food and Agriculture Organization of the United Nations (FAO), November 2007

12 Williams, M., Pehu, E. and Ragasa, C. (2006) Functional foods: Opportunities and challenges for developing countries. ARD (Agricultural & Rural Developments) *Notes*, Issue September 2006

13 Ismail, A. (2006) India: The land of opportunity, *Functional ingredients magazine*, January 2006

14 Subirade, M. (2007)

15 National Research Council (2008) Production of probiotic bacteria using maple sap. Biotechnology Research Institute, National Research Council, Canada, IPSO 11914

1.0 Emerging and future trends

The global food industry has shown consistent growth over the past several years and is expected to be influenced by significant market forces. In this section, we explore emerging and future trends that are likely to influence the food industry during the next two decades.

Rising demand due to demographic and economic change

Impacts of changing lifestyles, graying societies, and global demographics

More than 6.7 billion people live in the world today. The global population is increasing by about 80 million per year, and according to projections by the United Nations, it is expected to reach 9 billion by 2050.[16] Medical advances, an aging population, and higher standards of living are contributing to a continued rise in the number of mouths to feed and creating new challenges for the food industry. As a result, new and sustainable ways of producing high-quality food are needed.

Medical advances are leading to longer, healthier lives. Lifestyle choices also affect health status. However, unbalanced diets among many continue to cause heart- and obesity-related diseases, which are becoming significant causes of avoidable deaths in most developed countries. Moreover, slowing birth rates and longer life expectancy in Europe, Japan, and the United States have led to rapidly aging populations that are expected to demand more healthful and specialized food products.

The demand for high-quality and varied food is expected to increase in the coming years because of strong economic growth rates in developing countries, which have significantly raised living standards. Incomes in Europe and North America are also rising, albeit at a slower pace.

These changes present both challenges and opportunities to the agricultural and food industries, as they seek to improve quantity, quality, and health-promoting properties of crops and food products.

Increased demand for animal protein in developing countries

The livestock sector has faced increasing pressure to satisfy the growing global demand for high-value animal protein. The world's livestock sector is growing at a brisk pace, in step with growing population, income, and urbanization. Annual meat production worldwide is projected to increase from 218 million tons in 1997 to 376 million tons by 2030.[17] As presented in Table 5, world production and consumption has grown significantly in the past decade. For example, the global production of broilers and turkeys increased 38 percent between 1999 and 2008, faster than the growth in population over the same period. Milk production grew 15 percent over the same period.

Table 5 — World supply and utilization of livestock and products (million tons)

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Beef and pork										
Production	139.2	139.6	141.1	146.0	148.7	152.6	157.3	157.8	156.1	158.0
Consumption	139.4	139.3	140.7	145.9	148.8	152.1	156.5	156.8	155.5	157.5
Exports	9.1	9.0	9.1	10.2	10.7	11.4	12.3	12.7	12.8	13.1
Broilers and turkeys										
Production	55.1	57.9	60.0	62.3	63.1	64.6	67.8	68.8	72.9	76.0
Consumption	54.9	57.4	59.1	61.6	62.5	63.8	67.1	68.5	72.6	75.4
Exports	4.8	5.2	6.0	6.2	6.5	6.6	7.4	7.1	7.8	8.3
Dairy										
Milk production	383.0	389.4	394.4	405.3	409.6	415.7	421.4	427.8	435.7	439.6

Source: USDA Agricultural Outlook/Statistical Indicators 2008s

16 United Nations Population Fund (2007) State of world population 2007: Unleashing the Potential of Urban Growth. United Nations Population Fund.

17 World Health Organization (2008) Global and Regional Food Consumption Patterns and Trends. World Health Organization, 1211 Geneva 27, Switzerland

Table 6: Per capita consumption of livestock products (kg per year)

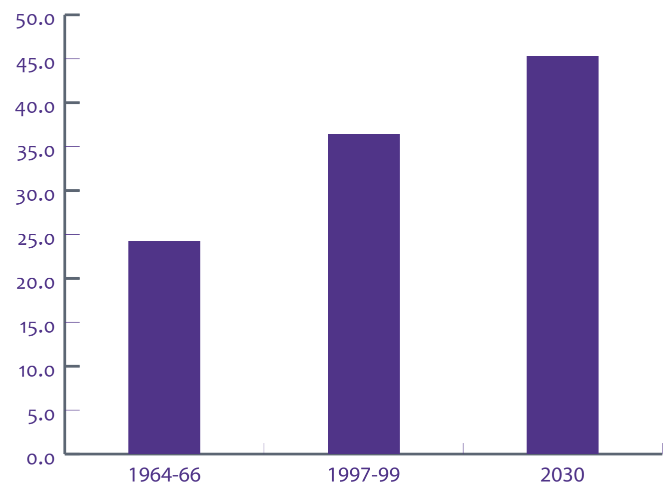
Region	Meat			Milk		
	1964 - 1966	1997 – 1999	2030	1964 - 1966	1997 - 1999	2030
World	24. 2	36. 4	45. 3	73. 9	78. 1	89. 5
Developing countries	10. 2	25. 5	36. 7	28	44. 6	65. 8
Near East and North Africa	11. 9	21. 2	35	68. 6	72. 3	89. 9
Sub-Saharan Africa (Excluding South Africa)	9. 9	9. 4	13. 4	28. 5	29. 1	33. 8
Latin America and the Caribbean	31. 7	53. 8	76. 6	80. 1	110. 2	139. 8
East Asia	8. 7	37. 7	58. 5	3. 6	10	17. 8
South Asia	3. 9	5. 3	11. 7	37	67. 5	106. 9
Industrialized countries	61. 5	88. 2	100. 1	185. 5	212. 2	221
Transition countries	42. 5	46. 2	60. 7	156. 6	159. 1	178. 7

Source: World Health Organization

Although consumption of animal proteins in developing countries increased steadily during the last 40 years of the 20th century — from 9 to 20 grams per capita per day — there is still significant potential for growth.[18] As indicated in Table 6, annual meat consumption in developing countries is projected to increase more than 47 percent from 1999 to 2030, compared with a 13 percent increase in industrial countries.[19]

Though calories derived from cereals have increased in absolute terms, they continue to fall as a share of total calories in developing countries, from 60 percent in 1963 to an expected 50 percent in 2030. Similarly, the contribution of other traditional staples, including potatoes, sweet potatoes, cassava, plantains, and other roots, dropped from being the second-largest contributor to dietary calories at 10 percent in the early 1960s to being the lowest at 6.2 percent in 1999. By that year, animal products had become the second major source of calories in developing countries, accounting for 10.6 percent of calories consumed.[20] Moreover, as Figure 2 illustrates, annual per capita meat consumption is expected to double between 1964 and 2030.

Figure 2: Annual per capita world meat consumption (kg / year)



These changes in consumption patterns are fueled by increasing income in developing countries, leading to even more demand for higher-quality foods, such as meat, eggs, and milk. Combined with sizable population growths, livestock producers are likely to see continued large increases in the total demand for animal products in those countries.[21]

Global convergence in food consumption and delivery systems

Income growth and globalization of the food retail and food service industry are creating similar food consumption patterns across the world. There is more convergence in food delivery systems as a result. The benefits and problems of modern food delivery are becoming global.

Food consumption patterns of middle- and high-income countries, as indicated by their food spending across different food types over time, are converging.[22] The expansion of Western-style retail and food-service outlets

18 United States Department of Agriculture (2008)

19 Organization for Economic Co-operation and Development (2007) Agricultural Outlook: 2007-2016. © OECD/FAO 2007

20 Bruinsma, J., (2003) World Agriculture: Towards 2015/2030 an FAO Perspective. Earthscan Publications Ltd London (FAO paperback)

21 World Bank (2006) Human Appropriation of the World's Food Supply. The World Bank, Washington, D.C.

22 Regmi, A., Takeshima, H., and Unnevehr, L. (2008) Convergence in Global Food Demand and Delivery. *Economic Research Report* Number 56, March 2008. A Report from the Economic Research Service, USDA

is modernizing the food marketing sector in developing countries. The USDA estimates that by 2025 food purchases in middle-income countries through Western-style grocery stores will approach 50 percent of the level of sales in higher-income countries.[23]

Convergence in the food service sector is also moving more quickly, with expenditures in middle-income countries expected to reach 50 percent of the level of high-income countries within a decade. This trend has implications for obesity and health in developing countries. USDA research on U.S. food consumption shows that foods eaten in restaurants are, on average, higher in calories and lower in nutrients than foods eaten at home.[24]

More broadly, the global convergence in food expenditures is likely to spur the already strong demand in developing countries for higher-valued food products. As market opportunities for agricultural producers, distributors, and retailers grow in these countries, regulations and standards for food safety and quality are likely to become increasingly important.

Innovative food products and concerns about safety and cost

Developing and marketing innovative food products will remain the lifeblood of the food industry. The current leading drivers of product innovation in the food sector are in health and wellness, performance improvement, and convenience. Growing social concerns about the impacts of consumer products on individuals, society, and the environment are driving fundamental regulatory changes. Food industries increasingly face a dizzying array of national, regional, and local regulations that govern the ingredients, formulations, packaging, pricing, and even promotions they can use.

Value for money is also a driving concern. There is an increasing reemphasis on low-cost, safe, high-quality food. This is expected to be stronger in the current economic downturn. New and innovative ways of improving production efficiency are likely to gain interest among researchers and producers.

Emphasis on health and wellness derived from food

Increasing demand for health and wellness through foods

In a fiercely competitive grocery market, where sales of established packaged food and beverages continue to stagnate, health and wellness is becoming a key growth area within the food industry. Moreover, as the oversupply of food and the emergence of private labels further create competition in the food retail market, health and wellness can be a significant product differentiator.

Globally, health and wellness food and beverages outperformed the overall sector's growth rate by approximately 12 percent between 2002 and 2005.[25] Certain key categories, such as organic and fortified/functional foods, saw even higher growth rates of 50 to 70 percent during the same period.[26] Today, global sales of health and wellness products exceed $420 billion. The largest growth areas are in Western Europe and Japan, although emerging markets of Brazil, Russia, India, China, and Mexico are also starting to see healthy growth.

Major drivers of this trend in the food industry include greater emphasis on healthy living in industrialized societies, the graying of the population in the developed world and its keen interest in health, and the increasing prevalence of illness and disease associated with high-fat and high-cholesterol foods in emerging and industrialized economies. These trends have led food manufacturers to invest in research to develop new products and to reformulate existing products to include more whole grains and fiber, as well as fortified nutrients, such as calcium, magnesium, potassium, and the new functional ingredient, omega-3. Even the global pet food market has headed toward "natural," "functional," and "healthy" products.

As these trends continue, the health and wellness segment of the food industry is likely to continue growing in the future.

Increasing demand for functional foods

Functional foods fall into a gray area between conventional foods and medicine. The World Bank defines functional foods as "food-type products that influence specific physiological functions in the body, thereby providing benefits to health, well-being or performance, beyond regular nutrition, and are marketed and consumed for this value-added property."[27] The U.S. Food and Drug Administration (FDA) does not currently have a definition nor a specific regulatory rubric for foods marketed as "functional foods." Instead, they are regulated the same as conventional foods under the authority of the Federal Food Drug and Cosmetic Act.

The growing market for functional or health-enhancing foods has emerged as a response to global demographic trends, patterns of health and disease, and innovation in food and health-related research. In developed countries,

23 Frazão, E., Meade, B., Regmi, A., (2008) Converging Patterns in Global Food Consumption and Food Delivery Systems. *Amber Waves*, February 2008 Edition, USDA-Economic Research Service

24 Regmi, A., Takeshima, H., and Unnevehr, L. (2008)

25 Agriculture and Agri-Food Canada (2007) Health and Wellness Trends for Canada and the World. Canadian Agri-Food Trade Service, http://www.ats.agr.gc.ca. Retrieved on July 24, 2008.

26 Agriculture and Agri-Food Canada (2007)

27 Kotilainen, L., Rajalahti, R., Ragasa, C., and Pehu, E. (2006)

with graying of the population and the increasing prevalence of lifestyle-related diseases, many use functional foods to promote health. In developing countries, similar demographic and public health trends are evolving among higher socioeconomic groups.

One particularly promising category of functional foods — or nutraceuticals — is probiotics, or "good bacteria," which sometimes are already present in food, and more recently, can be added to foods.[28] Scientists are now studying the use of probiotics in the prevention of colon cancer and are investigating the cholesterol-lowering effect from cultured dairy products. Growing domestic markets and the possibility of exports to the dominant markets of Europe and Japan provide economic opportunities in this sector.

Customized foods to match individual health needs

The science of nutrigenomics offers the promise of allowing health-conscious consumers to access information about the relationships between the foods they eat and their own metabolism. Matching specific foods or food choices with an individual's specific health needs is the future of nutrition practice. Such customization has been a goal of nutrition research for years. Recent convergence of information from the basic, applied, and social sciences now appears to offer tools that can enhance available products and services. Federal guidelines have already begun incorporating such information into population-based recommendations and are likely to continue to do so.[29] The food industry is likely to continue to develop and market products to meet the needs of diverse segments of the population.

Concurrent proliferation of competing "breeds" of food

Acceptance for genetically modified food

Since the introduction of agricultural biotechnology, farm crop yields have increased dramatically in the United States. That trend is expected to continue as biotechnology enables farmers to produce more corn, soybeans, and other foodstuffs on the same number of acres.

In the near term, bans on genetic modification of crops in the European Union and Japan are expected to keep demand for conventionally grown foods strong. In the future, though, a variety of factors — among them globalization, population growth, rising income levels, increasing competition between genetically modified and non-genetically modified food exporters, and concern about soaring world food prices — may relegate concerns about genetically modified foods to a local policy level. Moreover, because of scientific research, technology improvements, and new regulations, many stakeholders increasingly agree that food and food ingredients derived from currently available genetically modified crops are not likely to present a risk to human health.

While the focus of the first "generation" of biotech crops has been on the considerable economic benefits to farmers, evidence is growing that biotechnology has significant food safety and environmental benefits as well. This may further increase worldwide acceptance and demand for genetically modified foods.

Increasing demand for organic meat and dairy products

While there is greater acceptance of genetically modified foods, there is also a concurrent and growing interest in natural and organic products. Organic agriculture has a reputation for catering to a luxury niche, whose customers can afford to shop in more expensive health-food stores instead of discount retailers. However, the market is expanding beyond luxury buyers to those who have more interest in food quality and safety. Organic supply is now the world's fastest growing food sector, increasing at 15 percent a year during the past decade and worth roughly $40 billion in 2006, or 2 percent of food retail sales.[30]

By one estimate, steady growth is expected to continue across all segments, particularly meats, which represented 6 percent of total U. S. natural and organic foods in 2006.[31] The growth in organics is expected to supplant the growth of natural foods, as producers convert natural to organic to take advantage of new federal regulations and attention on organic foods.[32] However, economic downturns may curtail spending on higher-quality foods.

Leveraging productivity improvements

Higher crop yields through innovation

Projected increases in food demand, combined with limitations on the expansion of crop areas, are likely to drive cereal yields closer to the yield potential ceilings in many of the world's most productive cropping systems by 2025.[33] The ecological concentration of these high-production cropping systems is fundamental to achieving food security

28 Probiotics are "good" bacteria that help maintain the natural balance of microflora, organisms in the gastrointestinal (GI) tract. Probiotic microorganisms have been used as bacteria and yeasts for thousands of years to ferment foods.

29 Coulston, A. M., Feeney, M. J., and Hoolihan, L. (2003) The challenge to customize. *Journal of the American Dietetic Association*, Vol. 103, Iss. 4, Pages 443-444.

30 Citeau, C. (2007) Natural and Organic Food Market in North America. U. S. Agriculture and Food Branch, International Offices and Trade Division (IIAR), Government of Alberta, www. agrifoodalberta. ca. Retrieved on July 27, 2008.

31 *Ibid*.

32 Scialabba, El-Hage N. (2007) Organic Agriculture and Food Security in Africa. In: Proceedings of the Conference on "Can Africa Feed Itself?" Oslo, Norway, June 2007, FAO, pg. 6-8

33 Cassman, K. G. (1998) Ecological Intensification of Cereal Production Systems: Yield Potential, Soil Quality, and Precision Agriculture. In: *Plants and Population: Is There Time?* Proceedings of the National Academy of Sciences colloquium held December 5–6, 1998, at the Arnold and Mabel Beckman Center in Irvine, CA

under this scenario. Advances in biotechnology and other scientific areas are likely to be developed to meet the challenge. By 2025, global food security is expected to depend on rapid scientific advances in understanding the physiological basis of crop yield potential, the relationship between soil quality and crop productivity, and the role of environmental factors on plant ecology and crop yields.

Evolution of agricultural yields in developing countries

Food production in developing countries must rise by an estimated 2.5 percent per year to meet the needs of an increasing population and projected changes in diet.[34] Improving agricultural yields is critical to meet these needs. Genetic modification is a leading strategy among developing countries for increasing agricultural yields, although many concerns remain about its risks. As research addresses these concerns, the public may fully embrace genetically modified produce. Until then, alternatives to genetically modified crops are likely to be considered, specifically ones that do not involve as many challenges, questions, and controversies.

Proliferation of integrated plant nutrient systems

An integrated plant nutrition system, also known as integrated nutrient management, allows farmers to manage plant nutrition and soil fertility, taking advantage of the combined and harmonious use of organic, mineral, and biofertilizer nutrient resources to serve the needs of food production and to remain viable economically, environmentally, and socially.[35]

The global population is growing significantly and the amount of uncultivated arable land is rapidly decreasing. Because most of the additional food required must come from already-cultivated land, agriculture must intensify its operations with nutrient inputs that are optimal — high, but not excessive — and balanced. Even with a high degree of nutrient recycling through organics, mineral fertilizers will continue to be of central importance for meeting future food demands.

Future demand could be met in the long term if both crop management and soil fertility of the cultivated areas are improved. To do this, farming systems must increase the use of available local plant nutrient sources, as well as the consumption of mineral fertilizers. Worldwide, the use of mineral fertilizer nutrients is expected to increase from 142 million tons in 2003 to 199 million tons by 2030.[36] With this comes an increased concern about environmental issues.

Rapid global growth of aquaculture

According to the Food and Agriculture Organization,[37] aquaculture continues to grow more rapidly than all other animal food-producing sectors, with an average annual growth rate for the world of 8.8 percent per year since 1970, compared with only 1.2 percent for capture fisheries and 2.8 for terrestrial-farmed meat production systems. Freshwater culture continued to dominate, followed by mariculture and brackishwater culture.

Increase in no-till agriculture

No-till agriculture offers numerous benefits. It controls weed growth without plowing. It increases organic matter and decreases erosion, resulting in higher fertility and yields with lower fertilizer. Additionally, with the advances in cover crops and green manures, it can greatly reduce the use of high-cost herbicides. Given the combined environmental and economic benefits of the practice, no-till agriculture is likely to catch on around the world.

Agriculture as a global economic growth engine

Substantial empirical evidence shows the positive relationship between agricultural growth and economic development.[38] In industrialized countries and countries that are rapidly developing, agriculture has been the engine that contributed to growth in the non-agricultural sectors and to overall economic well-being.[39] Economic growth originating in agriculture can have a particularly strong impact on reducing poverty and hunger. According to the World Bank, GDP growth from agriculture raises the incomes of the poor as much as four times more than GDP growth from non-agriculture.[40] As a result, policymakers have shown renewed interest in promoting agriculture-based economic development strategies.

Global food security and nutrition

The international community today is paying more attention to hunger as an intrinsic and pressing development concern.[41] The issue has emerged more prominently in national antipoverty programs and similar initiatives, and there is more widespread and vocal acknowledgement that the persistence of chronic hunger in the midst of

34 Lal, R. (2006) Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development* Vol. 17 Iss. 2, pg. 197 — 209. Copyright © 2008 John Wiley & Sons, Ltd.

35 Roy, R. N., Finck, A., Blair, G. J., and Tandon, H. L. S. (2007) Plant nutrition for food security - A guide for integrated nutrient management. FAO *Fertilizer and Plant Nutrition Bulletin* 16. FAO, Rome, Italy

36 Food and Agriculture Organization (2008). Current world fertilizer trends and outlook to 2011/12. Rome, Italy

37 Food and Agriculture Organization (2007) The State of World Fisheries and Aquaculture 2006. FAO Fisheries and Aquaculture Department.

38 Valdes, A. and Foster, W., (2005) Reflections On the Role of Agriculture In Pro-Poor Growth, Paper prepared for the research workshop: The Future of Small Farms. Wye College, Kent

39 Alston, J. M., Norton, G. W., and Pardey, P. G. (1995) Science Under Scarcity: Principles and Practices for Agricultural Research Evaluation and Priority Setting, Cornell University, Ithaca, New York

40 World Bank (2008) *World Development Report 2008: Agriculture for Development*. The International Bank for Reconstruction and Development / The World Bank, Washington, D.C.

41 Skoet, J., and Stamoulis, K. (2006) The State of Food Insecurity in the World. FAO, Rome, Italy

plenty is an unacceptable contradiction. Rising world food prices, while contributing to the problem of hunger, also create opportunities for innovation and investment. A solid supply response from farmers in low-income countries could mitigate the prospects of growing food insecurity. World leaders are also influencing the global focus on food insecurity by committing themselves to an intermediate target of reducing the number of undernourished people by 2015 to half of the 1990 level.[42]

Regulatory constraints on biotech products

The regulatory approval process for new agricultural biotech products is regarded by many in industry as unduly slow and expensive, impeding the development of new technologies. The major laws regulating biotechnologies in the United States include the Plant Protection Act; the Federal Food, Drug, and Cosmetic Act; the Federal Insecticide, Fungicide, and Rodenticide Act; and the Toxic Substances Control Act.

These regulations have a mixed effect on the development and distribution of new products. In some cases, the rules appear to operate relatively efficiently, while in others they seem to facilitate anticompetitive behavior and associated inefficiency.[43] The framework for regulating biotechnology in other countries is similarly complex and managed across many agencies. Differences in regulations can impede trade in food and in other sectors of commerce. Some of these impediments reflect different circumstances and attitudes toward food safety.

The global regulatory framework is evolving in response to new developments and knowledge about food. Regulations are anticipated to address a wide variety of issues, including biosafety, antibiotic resistance, liability, and labeling. Governments must make decisions about the characteristics of the regulations, including whether to regulate ex ante or ex post, the specifics of registration requirements, and the "scope" of regulatory approval, for example, whether to regulate traits, events, or varieties.[44] These regulatory issues are likely to affect the development of technologies in the food industry.

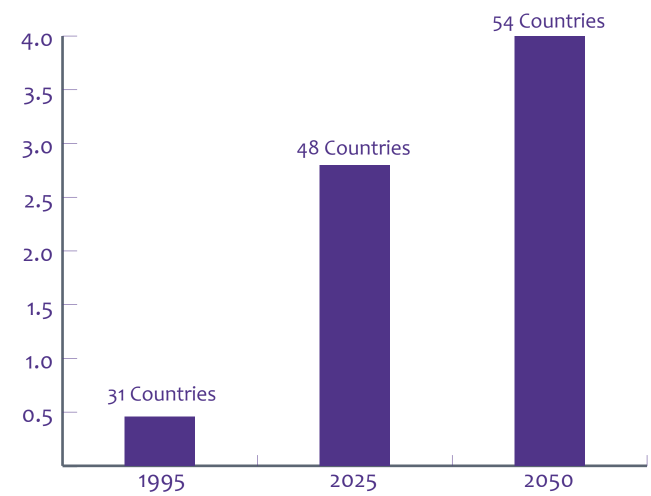
Resource constraints and degradation

Increasing concerns about water availability

The world is depleting its sources of fresh water. According to one estimate, by 2025, 64 percent of the world's population, estimated to be 8 billion by then, will live in water-stressed basins.[45] The Food and Agriculture Organization (FAO) predicts that additional water development is needed in order to accommodate another 2 billion people by 2030. An estimated 9,000 to 14,000 km^3 of water is economically available each year for human use.[46] Agriculture is the principal user of water resources, which include rainfall (so-called green water) and water in rivers, lakes, and aquifers (so-called blue water). It accounts for about 70 percent of all water withdrawals worldwide, compared to 10 percent for residential use and 21 percent for industry. The livestock sector is a key player in increasing water use, accounting for more than 8 percent of global human water use, mostly for the irrigation of feed crops.[47]

It is projected that by 2025, 33 percent of the world's population, or roughly 2 billion people, will live in countries or regions with absolute water scarcity (Figure 3).[48] Most countries in the Middle East and North Africa can be classified as having absolute water scarcity today. By 2025, these countries will be joined by Pakistan, South Africa, and large parts of India and China. This means that they will not have sufficient water resources to maintain their current level of per capita food production from irrigated agriculture — even at high levels of irrigation efficiency — if they also meet reasonable water needs for domestic, industrial, and environmental purposes.[49]

Figure 3: Population in water-scarce and water-stressed countries (in billions)



Adapted from: International Water Management Institute

To sustain their needs, water management efficiency is required. Among the absolute water-scarce countries listed above, all except South Africa may have to import a

42 United Nations (2007) The Millennium Development Goals Report 2007. Published by the United Nations Department of Economic and Social Affairs DESA - June 2007, United Nations, New York

43 Just, R. E., Alston, J. M., Zilberman, D. (2006) *Regulating Agricultural Biotechnology: Economics and Policy* http://www.myilibrary.com.floyd.lib.umn.edu/Browse/open.asp?ID=72461&loc=353. [Retrieved on August 1, 2008]

44 Just, R. E., Alston, Julian, M., Zilberman, D. (2006) *Regulating Agricultural Biotechnology: Economics and Policy* http://www.myilibrary.com.floyd.lib.umn.edu/Browse/open.asp?ID=72461&loc=353. [Retrieved on August1, 2008]

45 Steinfeld, H., et al. (2006) Livestock's long shadow - Environmental issues and options. The Livestock, Environment & Development Initiative. FAO/World Bank/EU/IFAD Sponsored Report

46 Kijne, J. W. (2003) Unlocking the water potential of agriculture. FAO, Rome, Italy

47 Steinfeld, H., et al. (2006)

48 International Water Management Institute (2002) Projected Water Scarcity in 2025. International Water Management Institute

49 Kumar, C. P. (2003) Fresh Water Resources: A Perspective. National Institute of Hydrology, India

substantial portion of their cereal consumption by 2025. Even countries with sufficient water resources to meet their current needs will have to develop their water supplies by 25 percent or more.[50] This will mean embarking on large and expensive water-development projects. For many countries, especially those in sub-Saharan Africa, it will be difficult to mobilize the necessary financial and other resources to achieve this goal.

Globally, the International Water Management Institute (IWMI) predicts that, to meet the 2025 water needs, the world must develop 22 percent more primary water supply. The irrigation sector, which is by far the largest water user today, is expected to account for 69 percent of the total primary water supply. To meet food needs, the primary water supply for irrigation must be increased by 17 percent.[51] IWMI's conclusion is that, while the world must continue investing in water development projects to meet future food demands, investments in research to improve crop water productivity could be a cost-effective way to limit the need for new dams.

Addressing water availability, reliability, quality, and price are challenges food producers, processors, researchers, and policymakers are likely to navigate in the near future. Action needs to be taken soon, given the time required to develop consensus on policy decisions that affect the global water system, infrastructure development for water conservation, modification of water-consumption behaviors, and development of technologies to produce develop drought resistance in crops.

Increasing concerns about soil quality

Worldwide, more than 99.7 percent of human food calories come from the land.[52] The livestock sector is by far the single largest user of land for human food, with a grazing area equivalent to 26 percent of the earth's ice-free, non-ocean surface. In addition, the total area dedicated to feed-crop production amounts to 33 percent of total arable land.[53] In all, livestock production accounts for 70 percent of all agricultural land and 30 percent of the land surface of the planet.[54]

Sustainability of these agricultural lands requires a better understanding of soil ecosystems, which is a complex area of study. Soil ecology is one of the last major unexplored disciplines in agriculture-related science, and it is particularly relevant to biodiversity. Soil organism populations are dynamic in nature and easily affected by the physical disturbance from tillage and by the chemical disturbance from fertilizers and pesticides.

Agricultural lands are under increasing pressure to dispose of large amounts of organic material used to maintain soil structure during intensive crop management. Moreover, the accumulation of heavy metals from pesticides, fertilizers, or other agrochemicals creates long-term risks for soil organisms and food safety. Increasing scarcity of water is likely to increase focus on soil management to improve water retention and use, particularly in conjunction with irrigation programs.

Depletion of world's fish stocks

The status of the world's fish populations and the health of its oceans are at risk. Recent research suggests a global collapse of currently harvested fish species by the mid-21st century if current fishing trends continue.[55] Even today, it is estimated that more than 90 percent of large fish in the ocean are gone.[56] Overall, more than 75 percent of world fish stocks (for which assessment information is available) appear already fully exploited or overexploited and are depleted or recovering from depletion. This reinforces earlier observations that the maximum potential of wild capture from the world's oceans has probably been reached, a fact that calls for a more cautious and closely controlled management of world fisheries.[57]

This scenario does not bode well for the food industry and global food security. Protein-energy malnutrition is likely to increase for most families in the developing world who are dependent on ocean fishing for their livelihoods.

Risks to input availability

Climate change affects water availability and distribution

Climate change and its potential implications for agricultural water use create increasing uncertainty for planning. Adapting to climate change will require ongoing review of its impact on population growth and land and water use, the effectiveness of water demand-and-supply programs, and the capacity of emerging technologies to deal with the challenges it presents. Not only is agriculture likely to be one of the victims of climate change, it is also a contributor to the problem because of its own greenhouse gas emissions.

Water availability is expected to be highly sensitive to climate change. Changes in rainfall can affect soil erosion rates and soil moisture, both of which are important for crop yields. The United Nations' Intergovernmental Panel

50 Scanes, C. G., and Miranowski, J. A. (2004) Perspectives In World Food and Agriculture, Ames, Iowa: Iowa State Press

51 International Water Management Institute (2002)

52 Pimentel, D. (2007) "Agriculture." In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). Published in the Encyclopedia of Earth, July 6, 2007. Retrieved on August 1, 2008.

53 Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., and de Haan, C. (2006)

54 *Ibid*.

55 Worm, B., et al. (2006) Impacts of Biodiversity Loss on Ocean Ecosystem Services. *Science* Vol. 314. no. 5800, pg. 787 – 790.

56 Myers, R., and Worm, B. (2003) 'Rapid worldwide depletion of predatory fish communities', Nature, vol. 423, pg. 280-283

57 Food and Agriculture Organization (2007) The State of World Fisheries and Aquaculture 2006. FAO Fisheries and Aquaculture Department.

on Climate Change predicts that while precipitation will increase in high latitudes, it will decrease in most subtropical land regions — by as much as 20 percent in some areas.[58] The enduring changes in climate, water supply, and soil moisture could adversely affect crop production in certain parts of the world. In North America, while regional precipitation will vary, the number of extreme precipitation events is predicted to increase.[59]

Climate change and regional agricultural systems

Climate change can significantly increase production risk and rural vulnerability, particularly in regions that already suffer from chronic soil and water resource scarcity or high exposure to climatic extremes, such as droughts and flooding. All of these can lead to poverty and hunger.[60] The effects of climate change on world agriculture may depend not only on changing climate conditions, but also on the agricultural sector's ability to adapt through changes in technology and demand for food, coupled with management of water availability, soil quality, and crop selection.[61]

Several factors directly connect climate change and agricultural productivity,[62] including average temperature increases, changes in rainfall amount and patterns, and the potential increase for more variable or extreme climatic events. In North America, moderate climate change can increase yields of rain-fed agriculture, but with smaller increases and more variability among regions than early estimates predicted, according to a 2007 working group report from the United Nation's Intergovernmental Panel on Climate Change.[63] The working group found that most studies project likely climate-related yield increases of 5 percent to 20 percent in North America during the first decades of the century, with the overall positive effects of a warmer climate persisting through much or all of the 21st century. Climate change is expected to improve growing conditions for some crops that are limited by length of growing season and temperature, such as fruit production in the Great Lakes region and eastern Canada. Still, the effects are expected to be mixed, with some areas suffering significant loss of comparative advantage. The U.S.'s Great Plains and Canadian prairies are expected to be particularly vulnerable. Additionally, crops that are currently near climate thresholds, such as wine grapes in California, are likely to suffer decreases in yields, quality, or both.

Agriculture in developing countries is expected to be more vulnerable to climate change than industrialized countries, especially in the tropics, where farmers may have limited resources enabling them to adapt to the expected changes.[64] Agricultural productivity in Asia and Africa are likely to suffer severe losses because of high temperature, severe drought, flood conditions, and soil degradation. Food security of many developing countries in these regions would be under tremendous threat.[65] The fishing industry is likely to be particularly vulnerable. Large-scale changes in the productivity of warm-water and cool-water fish are likely to affect fishing in many Asian countries. A rise in sea level would cause large-scale inundation along the vast Asian coastline and recession of flat sandy beaches. Irrespective of whether climate change will cause more frequent or more intense extreme events, it is apparent that many aspects of African economies are still sensitive to climatic hazards.

Concerns about pollution

Environmental impact of fertilizer use

Despite the increasing concerns about the adverse environmental effects of fertilizer, its use will remain an essential strategy to ensure food security and to protect the natural resource base. In the future, however, fertilizer use may demand a different approach — one that emphasizes growth with management rather than growth per se, so that the broader goals of food security, agricultural growth, and environmental protection are not sacrificed.[66]

Food contaminants and waste disposal

A variety of chemicals, including veterinary drugs, pesticides, and contaminants may leave residue in food. Toxic substances may occur naturally, such as aflatoxins, mycotoxins, and marine toxins, or they may be manmade and added to food intentionally, such as antibiotics, preservatives, and colorants. At times, food may be unintentionally contaminated by chemical hazards that include metals, cleaning agents, pesticide residues, animal drugs, other agrochemicals, and packaging materials used to keep food safe and fresh. Unintentional contamination may also occur from pollution of the water, air, or soil.[67]

Public concerns are growing about chemical residues in food, particularly substances with long-term toxicities yet to be evaluated. Those include endocrine disruptors or

58 Intergovernmental Panel on Climate Change (2007) Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Parry, Martin L. , et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pg. 1000

59 Intergovernmental Panel on Climate Change (2007)

60 Food and Agriculture Organization (2008) Climate Change Adaptation and Mitigation: Challenges and Opportunities for Food Security. In: Proceedings of High-Level Conference on World Food Security: The Challenges of Climate Change and Bioenergy. Rome, Italy.

61 Intergovernmental Panel on Climate Change (2007)

62 United States Climate Change Science Program (2008) The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States: Synthesis and Assessment Product 4.3 Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Convening Lead Authors: Peter Backlund, Anthony Janetos, and David Schimel. Managing Editor: Margaret Walsh

63 Intergovernmental Panel on Climate Change (2007)

64 United States Climate Change Science Program (2008)

65 Intergovernmental Panel on Climate Change (2007)

66 Bumb, B. L., and Baanante, C. A. (1996) Policies to Promote Environmentally Sustainable Fertilizer Use and Supply to 2020. IFPRI. A 2020 Vision for Food, Agriculture, and the Environment

67 Etzel, R. A. ed. (2003) Pediatric environmental health, 2nd ed. Elk Grove Village, IL, *American Academy of Pediatrics*, pg. 165–180

other chemicals with toxic effects to reproductive organs.[68] This situation is likely to increase international trade regulation and create trade barriers. It is also likely to add extra production costs to food industries with increased regulatory requirements.

As farm and herd sizes increase, the large volume of manure generated in relatively small areas creates challenges. Research and product development are likely to increase for odor control, waste disposal, nutrient application, feed additives, etc. The economics of environmentally sensitive waste disposal can impact many farmers. Producers are expected to pay for these improvements, and at least some costs could be passed on to consumers.

Environmental sustainability of food production and processing

Environmental footprint of production and processing

Changes in the food systems have significant environmental costs. The farther food travels from farm to fork, the higher are fossil fuel consumption and greenhouse gas emissions.

Moreover, intensive agriculture directly contributes about half of the global emissions of two of the most potent non-carbon dioxide greenhouse gases: nitrous oxide emissions (from fertilizer application and manures) and methane (from enteric fermentation in livestock production), according to the World Bank's 2008 report on agriculture. Each accounts for about one-third of the farm sector's total non-carbon dioxide emissions and these are projected to rise with increased meat consumption in emerging economies.[69]

A carbon footprint is the amount of greenhouse gases, measured in units of carbon dioxide, produced by human activities. Worldwide, agriculture contributes nearly 14 percent of total greenhouse gas emissions.[70] In the United States, food production accounts for 17 percent of total fossil fuel consumption.[71] The carbon footprint of an average American diet is 0.75 tons CO2-equivalent per annum, without accounting for transportation from farm to market.[72]

Meat products have a larger carbon footprint than fruits, vegetables, and grains. The carbon footprint of the average meat eater is approximately 1.5 tons CO2-equivalent more than that of a vegetarian.[73] Increasing concerns about the carbon footprint of food products are likely to spur changes in product labeling, certification of sustainable practices, and, if pursued seriously, significant changes in food production technology.

Trade-offs between carbon sequestration and food production

Growing concern about global climate change has spurred interest in several options for reducing greenhouse gas emissions and mitigating climate change impacts on human, animal, agricultural, and natural ecosystems. Areas of interest include using perennial grasses to generate bioenergy and sequestering organic carbon in agricultural soils.

Carbon sequestration crop systems can, if properly designed, yield significant environmental and social benefits. The right choice of biomass crops and production methods can lead to favorable carbon and energy balances and a net reduction in greenhouse gas emissions. Land conversion from food crops to carbon sequestration crops represents a tradeoff between food and carbon sequestration crops. Managing this trade-off requires policy development based on broad stakeholder participation.

Globalization of production and processing

Increased trade of processed foods

Processed food sales are a major segment of global food and contribute $3.2 trillion to the world food market.[74] Exports of processed agricultural products grew 6 percent per year from 1981 to 2000, compared with 3.3 percent for primary products.[75] Growth rates have been high — above the average of 6 percent — for the processed forms of cereals, fruits, vegetables, pulses / legumes, tropical beverages, and poultry products.

Globally, processed and semi-processed food and agricultural products now account for two-thirds of total agricultural trade.[76] The fastest growing component of U.S. agricultural exports has been processed food products.

As the global food and agriculture system rapidly evolves, rising incomes and changing food consumption patterns are expected to affect growth in processed food trade worldwide. Consumer preferences, shaped primarily by incomes, changing lifestyles, and evolving cultural preferences, largely determine the items available in grocery

68 Vracko, P., et al. (2007) Dietary exposure to potentially hazardous chemicals in children's food. *Fact Sheet* No. 4.4, May 2007, Code: RPG4_Food_Ex1. European Environment and Health Information System. © 2007 World Health Organization

69 World Bank (2008) Adaptation to and mitigation of climate change in agriculture. In: World Development Report http://siteresources.worldbank.org/INTWDR2008/Resources/2795087119212387976/WDR08_15_Focus_F.pdf

70 Walser, M. (2008) Carbon Footprint. In: Encyclopedia of Earth. Eds. Cutler J. Cleveland Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment

71 *Ibid.*

72 *Ibid.*

73 *Ibid.*

74 Regmi, A. and Gehlhar, M., eds. (2005) New Directions in Global Food Markets. AIB-794, USDA/ERS, February 2005. Washington, D.C.

75 Food and Agriculture Organization (2004) The State of Agricultural Commodity Markets 2004. Rome, Italy

76 Regmi, A., and Gehlhar, M. (2005) Processed Food Trade Pressured by Evolving Global Supply Chains. Amber Waves, Vol. 3 (1) Economic Research Service/USDA. Washington, D.C.

stores in different markets. The pace of liberalization in food and agricultural trade and the changing nature of investment and competition in the global food system are expected to affect trade patterns.

Multinational corporations and supply chains

The United States, the European Union, and Japan currently account for about two-thirds of global processed food sales. Meanwhile, developing countries account for more than three-quarters of total global food consumers. Given the growth in demand and projected food sales in those developing countries, multinational food retailers and manufacturers are expected to increasingly focus on those markets.[77]

The largest firms based in developed countries are expanding their sales in numerous foreign markets as growth in the home markets stagnates. Some firms, such as Nestlé, Kraft, and Unilever, already operate in more than 140 countries.[78] With young, growing populations in Asia and Latin America driving sales of baby foods, milk-based products, bakery products, and confectioneries, this trend is likely to continue, with manufacturing firms expanding to supply the emerging large-scale supermarket chains in these regions.

The expanding supermarket sector in developing countries is increasingly foreign-owned. In Latin America, large multinational firms, such as Ahold, Carrefour, and Wal-Mart, constitute 70 percent to 80 percent of the top five supermarket chains per country.[79] The presence of multinational retailers is likely to lead to an overall increase in food trade.[80]

The quest for year-round supply of fresh products has encouraged joint venture partnerships and strategic alliances among firms in the northern and southern hemispheres, increasing trade in these products. Similarly, alliances with retail outlets can open export opportunities for both small and large producers and manufacturers when the alliance is with a large multinational retail chain. However, by assuring a steady market locally, the presence of large multinational retailers may also encourage food manufacturers to expand their manufacturing units into the region. This may encourage more local processing from domestically produced raw products, reducing imports of processed foods.

77 Regmi, A. and Gehlhar, M. (2005) Factors Shaping Global Food Markets. In: Anita Regmi and Mark Gehlhar, (editors) New Directions in Global Food Markets, AIB-794, Economic Research Service/USDA

78 Regmi, A., and Gehlhar, M. (2005)

79 Regmi, A. and Gehlhar, M. eds. (2005) New Directions in Global Food Markets. AIB-794, USDA/ERS, February 2005. Washington, D.C.

80 Regmi, A. and Gehlhar, M. (2005)

Expanding economy spreads innovation

As the new global economy expands, major changes in the world's population and economy in coming decades offer the prospect for greatly expanded agricultural trade. Agro-processing has a high potential to boost economies based on agriculture and to ensure sustainable growth and stimulate rural incomes globally, especially in developing countries. As the new global economy rapidly expands, the worldwide distribution of agricultural products, countries are more likely to produce food in sufficient quantity and to enhance the competitiveness of agriculture worldwide by developing value-added foods based on higher quality standards and improved processing techniques.

As food companies extend their operations into developing countries, particularly China and India, a proliferation of food technologies is likely to flow to these countries. Collaborations between universities and research centers in both developed and developing countries can be expected to spur food technology innovations.

Globalization elevates concerns and risks

Concerns over safety of food imports

International trade in fresh and processed food is growing, for reasons that include an expanding world economy, freer policies governing food trade, growing consumer demands, developments in food science and technology, and improvements in transport and communications. This growth in trade may increase concerns about safety. Countries that import food should consider how they can enhance the safety of imported food. Meanwhile, access to food export markets will continue to depend on the exporter's ability to meet the regulatory requirements of importing countries.

Multiple strategies can work to improve confidence in food safety. These include sampling and testing imported food at the port of entry, requiring test results or inspection certificates, and allowing imports only from establishments that are compliant with the importing country's standards and regulations. Educating and training of food inspectors is also important.

Nationalistic concerns about food security

National governments and international organizations are taking steps to minimize the effects of higher international prices on domestic prices and to reduce the impact on particular groups. Some of these actions are likely to help stabilize and reduce food prices, but others may help certain groups at the expense of others or make food prices more volatile in the long run and seriously distort trade.

Many countries are taking steps recently to try to keep down prices of domestic farm products. China has banned rice and maize exports; India has banned milk powder exports; Bolivia has banned the export of soy oil to Chile, Colombia, Cuba, Ecuador, Peru, and Venezuela; and Ethiopia has banned exports of major cereals.[81] This nationalistic approach to the current global food security situation can have serious implications for the future of world food markets and agricultural trade.

Risk of animal epidemics and pandemics

Despite national and international disease control arrangements, outbreaks of epidemic diseases of livestock have become increasingly frequent in certain regions. Weaknesses of disease surveillance systems and the inability to control major diseases at their source may allow their spread across geographical borders. Food security is being threatened in many areas of subsistence agriculture. Several diseases, especially foot-and-mouth disease, have made fresh incursions in developed regions, such as Western Europe, where dense livestock populations make animals highly susceptible. The risks increase along with the growth of the international or transcontinental trade in animals and animal products, both legal and illegal.

Vulnerability to external shocks

A number of events, including war, natural disasters, industrial accidents, labor unrest, sudden closures by major suppliers, and terrorist attacks, can create disruptions in the food supply chain. The global food supply chain provides a particularly attractive target to terrorists because of the enormous potential economic consequences.

U.S. players alone cannot sufficiently reduce the vulnerability of the United States to such disruptions.[82] A recent report from the World Economic Forum identifies the vulnerability of the supply chain as a key risk that must be confronted through global collaboration. According to the report, "ultimately, effective management of global risks requires a collaborative and coordinated approach in public-private partnership at an international level. Given the macroeconomic and microeconomic impact of supply disruptions arising from a range of global risks, improved dialogue and policy on these risks is crucial to the effective management of the global economy."[83]

Civil unrest and wars also can affect the global food supply chain. The civil war in the Ivory Coast, for example, has disrupted the international market for cocoa. In a global marketplace, events in one area of the world can disrupt the food supply chain around the globe. Disruptions are inevitable. Companies that understand the vulnerabilities and that have developed and executed sensible business continuity strategies are more likely to prevail.[84]

Government approaches to risk management

Consumer welfare-based restrictions on trade

As the public becomes increasingly concerned about agriculture's impact on the well-being of society, attention is focusing on issues such as food safety and quality, environmental sustainability, and ethically appropriate methods of production. As a result, governments in many countries are being asked to impose more stringent rules and regulations over food.

Governments may respond to these concerns based on cultural and social values, as well as political systems. It is clear, however, that the search for cheaper food and greater economic efficiency are no longer accepted as the sole standards for measuring policy choices.

Given the importance of agricultural trade and the emerging differences in regulations, international conflicts over such policies could easily arise. Similarly, ethical conflicts are likely to emerge, particularly involving genetically induced changes in animal and plant life, and the impact of those on health and the environment.

Technical barriers to trade

The Organization for Economic Cooperation and Development (OECD) defines technical barriers to trade (TBT) as technical regulations and voluntary standards that set out specific characteristics of a product, such as its size, shape, design, functions, and performance, or the way a product is labeled or packaged before it enters the marketplace.[85] Included in this set of measures are also the technical procedures which confirm that products fulfill the requirements laid down in regulations and standards.[86]

The World Trade organization's (WTO's) agreement on technical barriers to trade aims to ensure that these measures are necessary. The agreement asks all members to adhere to disciplines for the elaboration, application, notification, and review of technical regulations, standards, and conformity assessment procedures.[87] WTO members have increasingly engaged in bilateral, regional, and multilateral free trade agreements and custom unions,

81 von Braun, J. (2008) Rising Food Prices: What Should Be Done? IFPRI Policy Brief April 2008. Washington, D.C.

82 Kelly, R. W. (2008) Chain of Perils: Hardening the Global Supply Chain and Strengthening America's Resilience. The Reform Brief-Advancing the Reform Agenda: The Reform Institute, March 6, 2008

83 World Economic Forum (2008), Global Risks 2008: *A Global Risk Network Report*, January 2008, Geneva.

84 Kelly, R. W. (2008)

85 Organization for Economic Co-operation and Development (2005) Looking Beyond Tariffs, The Role of Non-Tariff Barriers in World Trade, OECD, Paris

86 World Trade Organization (2007) Twelfth Annual Review of the Implementation and Operation of the TBT Agreement, *Note by the Secretariat*, G/TBT/21/Rev. 1

87 Lesser, C. (2007) Do Bilateral and Regional Approaches for Reducing Technical Barriers to Trade Converge Towards the Multilateral Trading System? OECD Trade Policy Working Paper No. 58. Trade and Agriculture Directorate Trade Committee; Working Party of the Trade Committee

which often include TBT provisions as well.[88] As these agreements proliferate, a country may often join several different regional, agricultural trade agreements. This is likely to create a slew of overlapping arrangements, which can, in turn, duplicate or contradict efforts to liberalize agricultural trade multilaterally. This is likely to affect food marketing systems where commodity-dependent countries would find exporting their produce increasingly difficult.

Country-of-origin labeling and trade

Country-of-origin labeling (COOL) of food is a potentially important aspect of consumer choice, which can decrease the perception of risk and preserve consumer confidence in the food system. The United States has moved slowly toward COOL during the past few years. Provisions of the Farm Security and Rural Investment Act of 2002, more commonly known as the 2002 Farm Bill, first required country of origin labeling for beef, lamb, pork, fish, perishable agricultural commodities, and peanuts. In January 2004, the U.S. Congress delayed implementation of mandatory COOL for all covered commodities, except wild and farm-raised fish and shellfish until September 2006 and later extended that by an additional two years.[89]

The recently enacted Food, Conservation, and Energy Act of 2008, known as the 2008 Farm Bill, expands the list of covered commodities. Experts do not agree completely on the impact of COOL on food safety, but there is a general consensus that it will shape consumer perception.

Increased regulation for food industry

Several food-related regulatory issues have been identified as drivers of food safety and technology development in the future[90]:

- ***Food nanotechnology*** may continue to be a hot topic, but the safety issues may take the forefront. Attention is expected to focus on consumer perceptions, with increasing interest from regulatory and standards agencies (FDA, the Codex Alimentarius Commission, etc.), the media and in turn, consumers. Significant research funds are likely to be dedicated to studying the toxicology and safety of nanoscale biomaterials.
- ***Product safety*** is expected to be a continuing concern for the public and regulators. Efforts are likely to focus on better on-farm management and the implementation of good agricultural practices.
- ***Chemical food safety*** issues are expected to increase. This is likely to include the review of ingredients that have long been considered safe, such as the GRAS list that is already under evaluation in Canada. Sodium chloride is a likely candidate. The prevalence and health impact of chemicals, such as acrylamide, are expected to continue to be debated.
- ***Trans fat labeling*** is in effect, but the topic is likely to continue to be newsworthy as regional and international bans on the sale of foods containing trans fats are likely to continue. It is likely that other states and countries may follow the complete ban imposed by California, which will take effect in 2010.
- ***Contamination of foods with non-food-approved genetically modified organisms*** may see increased concerns. Improved detection methods may result in increased detection of such incidents.
- ***Irradiation*** may have limited success in the marketplace in the foreseeable future, hampered as it is by negative public perception. Nonetheless, recent outbreaks of bacteria-causing disease in produce could result in increased authority for the FDA and increased FDA/USDA collaboration to expand use of irradiation.
- ***The environmental impact*** of products and new technologies is expected to be more heavily considered by industry. There is expected to be an increasing emphasis on full life cycle analysis when assessing the safety of foods and food packaging materials, along with the consideration of the entire "footprint" of the industry on the environment.
- ***Cloning*** is expected to continue as a significant concern. Although producer and consumer resistance is high and many question the need for such technology, there has been some indication that producers view the technology as promising.
- ***Food labeling*** to combat obesity is expected to continue the focus on calories and serving sizes.

Sustainability and extension of farm subsidies

Numerous studies have confirmed that whenever domestic farm subsidies are increased, they are quickly capitalized into farmland prices. A 2002 study for the USDA concluded that direct payments on land formerly dedicated to program crops affected the cash-rental rate a tenant was willing to pay for an acre of land, which in turn affected the land's price.[91]

According to C. Ford Runge, the Distinguished McKnight University Professor of Applied Economics and Law at the University of Minnesota, "the result of this insidious capitalization process is that a 20 percent to 25 percent

88 World Trade Organization TO RTA Gateway, http://www.wto.org/english/tratop_e/region_e/region_e.htm. Retrieved on August 22, 2008.

89 United States Department of Agriculture (2008) Country Of Origin Labeling. Agricultural Marketing Service, USDA, Washington, D.C.

90 Institute of Food Technologists (2007) Food Forecast 2007: Government Regulations & the Science of Food 2007. IFT Office of Science Communications & Government Relations. http://www.ift.org. Retrieved on August 1, 2008.

91 Roe, T., Somwaru, A., and Diao, X. (2002) "Do Direct Payments Have Intemporal Effects on U.S. Agriculture?" Paper presented at the USDA Conference on Decoupling (July 2002)

expansion in domestic subsidy spending will only insulate U.S. producers from global competition in the short run. Within a few years, by bidding up land rents, it will raise production costs and actually injure U.S. farm competitiveness. As the cost structure of farming rises, profit margins will fall, spurring farmers to demand yet higher subsidies. In other words, we will witness a vicious cycle of cost escalation and public spending that will push U.S. farmers further and further away from the competitive edge."[92]

Fiscal pressures faced by the governments may reduce the sustainability of these subsidies in the long run.

Managing commodity and energy prices

High price for grain and food commodities

The best available projections suggest that food prices are likely to remain high in the next few years, affecting most developing country markets. The resilience of the world's food system is expected to be severely tested in the next few years. Policymakers may have to return to thinking about food as a strategic asset and begin to modify food policies accordingly.[93]

High prices are likely to stimulate a supply-side response, in which market signals are transmitted to food producers who have capacity to increase production and supply the market if existing transport and infrastructure allow.[94] This may represent an important opportunity for promoting agricultural and rural development in many low-income countries, as long as policies and other supportive measures are established quickly.

The current state of global food markets appears to be shaped by the confluence of various forces that have created unique developments observed since 2006. Although it is difficult to quantify these factors, some studies have attempted the task. Among the most, important factors are[95]:

- ***The strengthening of linkages among different agricultural commodity markets.*** More connections among those markets, including grains, oilseeds, and livestock products, have resulted from rapid economic and population growth in many emerging countries. This trend is likely to continue and will affect the market dynamics both in developed and developing countries.
- ***The strengthening of linkages between agricultural commodity markets and other markets, such as fossil fuels***.
- ***The development of biofuels and financial instruments that influence not only the costs of production of agricultural commodities, but also their demand***.
- ***The depreciation of the U.S. dollar against many international trading currencies***. Most agricultural commodity prices are quoted in U.S. dollars, and the significant decline in its relative value over the recent years has critically affected agricultural markets.
- ***The impact of increasing frequency and magnitude of extreme weather***: Extreme weather has affected crop production in many countries. For example, severe drought in Australia, one of the world's largest wheat producers, has cut significantly into that global market.
- ***The reduction of food stock levels***. Since the mid-1990s, there has been a gradual reduction in the level of stocks, mainly of cereals. This supply-side factor has had a significant impact on current markets. Global stock levels have declined by an average of 3.4 percent per year as demand growth has outstripped supply. Production shocks at recent low stock levels, caused by war or other disruptions, helped set the stage for rapid price hikes.
- ***Rising energy prices***. High energy prices have made agricultural production more expensive, raising the cost of mechanical cultivation, inputs like fertilizers and pesticides, and transportation of inputs and outputs.[96]
- ***The changing structure of demand***. The growing world population is demanding more and different kinds of food. Rapid economic growth in many developing countries has strengthened consumers' purchasing power, generated rising demand for food, and shifted food demand away from traditional staples toward higher-value foods like meat and milk. This dietary shift is leading to increased demand for grains used to feed livestock.[97]

Energy prices

Rising energy prices pose a renewed challenge to global economic security. This is particularly true in agriculture, where inputs rely on energy resources and the sales of outputs depend greatly on energy-intensive distribution services. Animal production is also affected by rising feedstock prices.

Global consumption of marketed energy is projected to rise by 50 percent between 2005 and 2030.[98] Global energy

92 Runge, C. F. (2003) Agrivation. *National Interest*; Summer 2003 Issue 72, pg. 85, 9p

93 World Economic Forum (2008) Global Risks 2008: A Global Risk Network Report, January 2008, Geneva, Switzerland

94 Food and Agriculture Organization (2008) Soaring Food Prices: Facts, Perspectives, Impacts and Actions Required. In: Proceedings of High-Level Conference on World Food Security: The Challenges of Climate Change and Bioenergy, Rome, Italy. June 3 – 5, 2008

95 *Ibid.*

96 von Braun, J. (2008)

97 *Ibid.*

98 Energy Information Administration (2008) International Energy Outlook 2008 – Highlights. The Energy Information Administration. Report #:DOE/EIA-0484

demand is expected to grow in the long run, and given supply constraints, and despite the current downward trend in oil prices, oil prices are projected to persist at above-historical averages over the long term. Agriculture faces many important challenges in the new energy era and there may be significant vulnerability if energy costs rise over the long term.[99]

Demand for energy-saving technologies on farms

Electrical energy consumption in agriculture has been steadily rising because of increases in mechanization, use of confinement housing, and farm size. Agriculture in the United States consumes more than 2 quadrillion Btu (or 10,551 quadrillion Joules) of energy each year. Approximately 28 percent of that goes to fertilizer manufacturing, 7 percent to irrigation, and 34 percent to diesel- and gasoline-burning farm vehicles used to plant, till, and harvest crops. The remainder goes to pesticide production, grain drying, and facility operations.[100]

On-farm energy management has a huge potential for improving the environment, lowering farm and ranch production costs, and decreasing reliance on foreign energy supplies. According to the USDA, efficient on-farm energy management may include:[101]

- Reducing or eliminating tillage and managing residues to reduce fuel use and improve soil, water, and air quality. It is estimated that switching from conventional tillage methods to no-till can result in fuel savings of 3-9 gallons per acre.
- Adjusting nutrient management and crop rotations to include legumes to offset use of petroleum-based nitrogen fertilizers.
- Adjusting irrigation timing to directly reduce energy consumption, as well as other resource concerns.
- Using integrated pest management strategies to optimize petroleum-based inputs and produce environmental benefits. Precision application is likely to lead to better weed control, lower herbicide runoff, and energy savings.
- Planting perennial crops and introducing rotational grazing to reduce energy associated with planting and harvesting.
- Switching to more energy-efficient machinery, such as grain dryers, milk chillers, and irrigation pumps. Improvements in water efficiency of a modest 10 percent could reduce diesel consumption by 80 million gallons, or $192 million on irrigated farmland, according to some estimates.
- Converting agricultural biomass and waste to biofuels, such as ethanol and biodiesel, to directly reduce demand for petroleum-based liquid fuels and to potentially improve air quality.
- Recycling lubricants and other petroleum-based material to reduce demand for petroleum and offset potential environmental damage associated with other disposal means.
- Developing alternative energy sources, such as anaerobic digestion, solar, and wind, to directly substitute for purchased energy supplies and reduce carbon and greenhouse gas emissions.

Managing the impact of biofuels

Impact of biofuels on food production

Buoyed by government subsidies and, more recently, runaway fuel prices, biofuels production has grown rapidly in recent years. Between 2001 and 2007, for example, U.S. fuel ethanol production capacity grew 220 percent, to 6.1 billion gallons.[102] In the United States, the ethanol industry is supported by government subsidies, production targets, tax credits, regulation, and legislation that mandates ethanol production and creates financially attractive investment opportunities in ethanol production capacity.[103] For example, the federal government provided direct corn subsidies equaling $8.9 billion in 2005.[104] Further, energy legislation signed into law in 2007 calls for a seven-fold increase in domestic biofuel production by 2022.[105]

Rapid growth in biofuel production has raised concerns about the impacts on food production and climate change. Among the key concerns are deforestation, biodiversity loss and carbon release due to land use change, the availability of land and feedstock, and competition between biofuels and food production.[106] A common worry is that biofuels may divert agricultural production away from food crops, threatening food supplies, especially in developing countries. Feedstock makes up the principal share of total biofuel production costs, accounting for 50 percent to 70 percent of overall costs for ethanol and 70 percent to 80

99 Roland-Holst, D., and Zilberman, D. (2006) How Vulnerable is California Agriculture to Higher Energy Prices? *Agricultural & Resource Economics Update*. Vol. 9 No. 5 May/June 2006

100 Murray, D. (2005) Oil and Food: A Rising Security Challenge. Copyright © 2005 Earth Policy Institute, May 9, 2005-4

101 United States Department of Agriculture (2006) Conservation Resource Brief. *Energy Management*, No. 0608, Natural Resources Conservation Service, USDA, www.nrcs.usda.gov

102 Ethanol Statistics (2007) The United States Ethanol Market. *Ethanol Reports*: ©Ethanol Statistics 2008 http://www.ethanolstatistics.com

103 Ethanol Statistics (2007) The United States Ethanol Market. *Ethanol Reports*: ©Ethanol Statistics 2008 http://www.ethanolstatistics.com

104 Runge, C. F., and Benjamin, S. (2007) How Biofuels Could Starve the Poor. *Foreign Affairs*, 00157120, May/Jun2007, Vol. 86, Iss. 3

105 Government Accountability Office (2007) Independence and Security Act of 2007, Sec. 202, United States Government Accountability Office. GAO-07-713

106 von Braun, J. (2008) Biofuels, International Food Prices, and the Poor. *Testimony to the United States Senate Committee on Energy and Natural Resources*; Thursday, June 12, 2008. IFPRI, Washington, D.C.

percent of costs for biodiesel.[107] The extent of competition between crops for biofuels with food production remains a significant question.

Advances in biofuels technology

Technological advances hold the promise of mitigating the impact of biofuels on food production. Researchers are developing biocatalysts — enzymes, yeasts, and bacteria produced using biotechnology — that will allow ethanol production from just about any organic matter, or "cellulosic ethanol." Biotechnology also is being used to produce new, improved biofuels that will be blended at higher rates, will be transported through existing infrastructure, and will provide better fuel economy.

Such technological developments could affect the food industry in two ways. Alternative biofuel crops, and specifically a movement away from corn- or sugarcane-based ethanol and soybean-based biodiesel, are likely to slow the diversion of food crops for fuel. The developments may decrease or increase the pressure on land and water resources as the first generation of biofuels gives way to the second generation.

Increasing crop yields through biotechnology

The widespread adoption of plant biotechnology in major commodity crops in the United States has resulted in significant yield increases, savings for growers, and reduced pesticide use. Biotechnology has boosted the amount of grain produced per acre, for example. In 2007, the additional grain resulting from increased yields of biotech crops was enough to produce an extra 366 million gallons of ethanol.[108] This is important because farmable land is limited, yet the demand for grain for both food and fuel is growing dramatically. Crop yields are expected to continue increasing, allowing farmers to produce more corn, soybeans, and other foodstuffs on the same number of acres, thus, helping to provide sufficient supplies for both food and biofuels.

Workforce issues in the food industry

Limited supply of food scientists and technicians

The work of agricultural and food scientists plays an important part in maintaining the U.S. food supply by ensuring agricultural productivity and food safety. Food scientists and technologists usually work in the food-processing industry, at universities, or in the federal government to create and improve food products. They use their knowledge of chemistry, physics, engineering, microbiology, biotechnology, and other sciences to develop new or better ways of preserving, processing, packaging, storing, and delivering foods. Employment of agricultural and food scientists is expected to grow 9 percent between 2006 and 2016, from 33,000 to a projected 36,000.[109]

Agricultural and food science technicians are also needed to work with scientists to conduct research, development, and testing on food and other agricultural products. These technicians are needed to analyze, record, and compile test results, order supplies to maintain laboratory inventory, and clean and sterilize laboratory equipment. The U.S. Bureau of Labor Statistics estimates the number of technicians employed nationwide will increase from 26,000 in 2006 to 28,000 in 2016.[110]

The increasing share of processed food in emerging economies is expected to create demand for food professionals in emerging economies.

Aging of the farming population in developed countries

While U.S. agriculture has long been characterized by a larger share of older operators, the future of farming in America depends on continued entry by new farm operators. Overall, however, the number of U.S. farmers is declining and becoming older.[111] Meanwhile, the traditional pool of entrants into farming — white males in their twenties growing up on family farms — is shrinking as the number of farms decline and as farm families have fewer children.

Increases in labor productivity have been rapid enough to maintain farm output even in the face of these fairly strong declines. As a result, changes in the age composition and overall size of the farm population have not impaired the food security of the United States.[112] However, these shifts are likely to raise concerns about the structure of farming and the concentration of agricultural production worldwide.

Immigration policy for U.S. agriculture workers

The debate about an agricultural guest worker program has continued over the years. The policy of allowing temporary admission of aliens for seasonal farm jobs focuses on whether the supply of U.S. workers can sustain the widely fluctuating labor needs of some farmers and whether such a policy can hurt the prospects of domestic workers.

107 International Energy Agency (2004) Biofuels for Transport: An International Perspective. International Energy Agency, Paris.

108 Council for Biotechnology Information (2008) Agriculture Biotechnology: Increasing Crop Yields for America's Biofuels. Council for Biotechnology Information, 1201 Maryland Avenue S. W., Washington, D.C.

109 Bureau of Labor Statistics (2008) Agricultural and Food Scientists In: *Occupational Outlook Handbook*, 2008-09 Edition. U.S. Department of Labor

110 Bureau of Labor Statistics (2008) Science Technicians In: *Occupational Outlook Handbook*, 2008-09 Edition. U.S. Department of Labor

111 Hoppe, R. A., Ed. (2001) Structural and Financial Characteristics of U.S. Farms: 2001 Family Farm Report. *Agriculture Information Bulletin* No. 768, Resource Economics Division, Economic Research Service, USDA

112 United States Department of Agriculture (2002) Age of Farmers. *Briefing Rooms*. USDA, Economic Research Service, Washington, D.C.

The U.S. agricultural industry has, in recent years, legally recruited temporary migrant workers from Mexico.[113] Temporary farm workers make up one-third of the total U.S. agricultural labor force, but are over-represented in the production of labor-intensive crops, such as fruit, tree nuts, and vegetables. This labor market includes a relatively low-paid, heavily foreign-born, and frequently migrating population, an estimated half of whom lack the legal authorization to work in the United States.[114]

While technological advances and changes in labor costs may lower the agricultural sector's demand for hired labor overall, a growing consumer appetite for affordable fresh fruits and vegetables, and, in particular, more labor-intensive organic produce is likely to increase demand for temporary labor. These labor demands, as well as changes related to U.S. immigration policy, are likely to ripple through farm management decisions.

Local trends in demand and productivity

Community supported agriculture

Community supported agriculture is redefining the farmer-consumer relationship. The USDA and farmers' market advocates believe that direct marketing gives agricultural producers more profit-making opportunities, as well as other benefits. Consumers enjoy the opportunity to buy high quality, fresh products directly from the farmers at competitive prices. Such markets also foster links between the community and food production. This trend is expected to continue and could have significant impact on food systems and market dynamics.

Increasing U.S. demand for local food

The movement for local, environmentally sustainable farming has grown substantially over the last decade, as consumers have increasingly demanded fresh, local food.[115] A driving force behind this is consumer concern about "food miles," or the "farm to fork" distance food travels from where it is grown to where it is consumed. The average number of food miles for crops worldwide has steadily increased over the past 50 years. Studies estimate that processed food in the United States travels an average of 1,300 miles before being consumed, while fresh produce travels more than 1,500 miles.[116]

Food miles are a growing cause of concern because of the greenhouse gas emissions released through that transport. Overall, growing consumer interest in local and regional foods is creating new marketing opportunities for partnerships between consumers and farmers.

Antibiotic-free meat and dairy

Most farm animals in the United States today are dosed daily with antibiotics. The Union of Concerned Scientists estimates that 70 percent of all U.S. antibiotics are fed to healthy cows, pigs, and chickens as part of routine industrial meat and dairy production practices. This figure amounts to about 25 million pounds of antibiotics, or almost eight times the amount given to humans to treat disease.[117] An estimated 80 percent of U.S. cattle are treated with hormones to spur growth and increase feeding efficiency.[118]

Certain consumer segments and some public health organizations are increasingly concerned that the prolific use of antibiotics in animals is resulting in the creation of antibiotic-resistant strains of unwanted bacteria that may threaten human health. This trend is expected to create a significant niche market, though the recent economic downturn may decelerate growth in the short run.

Agriculture and urban sprawl

In an urbanizing environment, agriculture cannot remain distinctly rural or clearly separate from cities, even with agricultural land preservation. Farms in metropolitan areas are an increasingly important segment of U.S. agriculture, making up 33 percent of all farms, 18 percent of farmland, and one-third of the value of U.S. agricultural output.[119] Land development in the United States is generally moving in two directions: urban areas are expanding and large rural lots — greater than one acre per house — are being developed.[120] These represent marketing opportunities for food producers, but also increasing concerns of residential community about odors and water quality.

As residential or urban neighborhoods encroach on farmlands, local governments are increasingly active in managing issues, such as placing limits on the size of corporately owned animal-feeding operations.[121] Today's livestock and poultry facilities produce more animals, in more specialized buildings, on less acreage per animal than ever before. As the scientific evidence of public health risks from industrialized animal agriculture continues to increase, policy responses are emerging from a variety of sources, including corporate meat-purchasing policies and

113 Kandel, W. (2006) Meat Processing Firms Attract Hispanic Workers to Rural America, *Amber Waves*, Vol. 4, Issue 3, June 2006

114 Kandel, W. (2008) Hired Farmworkers a Major Input for Some U.S. Farm Sectors. *Amber Waves*, April 2008 Edition, Resource Economics Division, Economic Research Service, USDA

115 Hill, H. (2008) Food Miles: Background and Marketing. A Publication of ATTRA - National Sustainable Agriculture Information Service www.attra.ncat.org. Retrieved on August 1, 2008.

116 Hill, H. (2008)

117 Clancy, K. (2006) Greener pastures: How Grass-Fed Beef and Milk Contribute To Healthy Eating. Cambridge, MA: Union of Concerned Scientists

118 Clancy, K. (2006) Greener Eggs and Ham: The Benefits of Pasture-Raised Swine, Poultry, and Egg Production. Cambridge, MA: Union of Concerned Scientists

119 Heimlich, R., and Anderson, W. (2001) Development at & Beyond the Urban Fringe: Impacts on Agriculture. *Resources & Environment*, AER-803 Economic Research Service/ USDA, August 2001. Washington, D.C.

120 Heimlich, R., and Anderson, W. (2001)

121 Horne, J. (2000) Rural Communities and CAFOs: New Ideas for Resolving Conflict. Kerr Center for Sustainable Agriculture. http://www.kerrcenter.com/publications/CAFO.pdf. Retrieved on June 27, 2008.

the 2003 policy statement by the American Public Health Association.[122] Citizen responses have also taken various forms, including protests and court actions.

Similarly, the location of meat-processing units is under greater public scrutiny in some areas. Concerns include the increasing pool of antibiotic-resistant bacteria resulting from overuse of antibiotics, air quality problems, contamination of water bodies with concentrated animal waste, animal welfare problems from dense housing of animals, unpleasant odors, and significant shifts in the social structure and economy of many farming regions. These issues require attention from the meat-processing industry to ensure continued operations of existing sites and permits for new facilities.

Managing legitimate concerns and overreactions from urban residents and agricultural segments is a balancing act expected to become more prevalent in local governments.

Summary

In this section, we explored emerging and future trends that are likely to influence the food industry. The global food market has shown consistent growth over the past several years and is expected to be influenced by significant market forces.

Significant demographic and economic developments are increasing the demand for food. Population growth, increasing life expectancy, and economic growth are expanding the demand for food products. Economic growth in emerging economies and global convergence in food consumption are expanding demand for animal protein, dairy products, and processed foods. There is also increased demand for more healthful and specialized food products. There is an increasing reemphasis on economically priced, safe, quality food.

There is increasing emphasis on health and wellness derived from food. Demand for health and wellness from food is being driven by demographic and cultural factors: greater emphasis on healthy living in industrialized societies, the graying of the population in the developed world and its keen interest in health, and the increasing prevalence of illness and disease associated with high-fat and high-cholesterol foods in emerging and industrialized economies. Innovation in food products has built on these trends to develop the growing market for functional or health-enhancing foods. Matching specific foods or food choices with an individual's specific health needs is the future of the nutrition practice and food industry.

Increasing demand for food requires productivity improvements to leverage constant or declining inputs. Developed and developing agricultural systems are required to improve agricultural yields to meet growing demand for food. Genetic modification is a leading strategy for increasing agricultural yields, although many are concerned about its risks. Proliferation of integrated plant nutrient systems can improve plant nutrition and soil fertility and improve the productivity and sustainability of food production.

Resource constraints and degradation present a challenge to increase food production. Long-term water availability and reliability is at risk in many parts of the world. Water management infrastructure, improvements in the efficiency of irrigation systems, on-farm water management practices, and water efficiency in plants can improve water availability and efficiency. Increasing focus on soil management to improve water retention can be expected. The status of the world's fish populations and the health of its oceans are at risk. More cautious and controlled management of world fisheries is required.

Climate change poses significant risk to agriculture systems and food production. Water availability is expected to be highly sensitive to climate change. The enduring changes in climate, water supply, and soil moisture could adversely affect crop production in certain parts of the world. Climate change can significantly increase production risk and rural vulnerability, particularly in regions that already suffer from chronic soil and water resource scarcity or high exposure to climatic extremes, such as droughts and flooding. The agricultural sector's ability to adapt depends on changes in technology and demand for food, coupled with management of water availability, soil quality, and crop selection.

Managing climate change and environmental sustainability of food production and processing can be catalysts for modifying consumer and producer behavior and improving food production practices. Increasing concerns about the carbon footprint of food products is likely to spur changes in product labeling, certification of sustainable practices, and, if pursued seriously, significant changes in food production technology.

Increasing globalization of processed foods is expected to continue. Economic and demographic changes are creating higher trade volumes for processed food products. Large multinational corporations are expected to flourish in this space. However, large multinational retailers may also encourage local food manufacturing from domestically produced raw products. Demand for food scientists and technicians are expected to increase as a result.

Increasing globalization is also expected to elevate concerns and risks associated with the food supply chain. There may

122 Osterberg, D., and Wallinga, D. (2004) Addressing Externalities from Swine Production to Reduce Public Health and Environmental Impacts. *American Journal of Public Health*; 94(10): pg. 1703–1708. PMCID: PMC1448520

be increasing concerns about food safety and nationalistic concerns about food security and independence. Risks of epidemics associated with increased trade in animal and animal products need to be monitored. The food supply chain may also be increasingly vulnerable to man-made calamities and exogenous shocks.

Governments may respond with a range of actions to address concerns about food products. Governments may regulate food products more closely to respond to concerns. The regulations could affect food safety, ethics of biotechnology and nanotechnology, international trade, food labeling, and environmental sustainability. Governments may impose technical barriers to trade and country-of-origin labeling requirements.

Managing high energy and commodity prices is increasingly important for food production. The strengthening of linkages between agricultural commodities, between agricultural commodities and energy markets, development of biofuels, reduction in food stock levels, increasing frequency and magnitude of extreme weather, and higher demand for food commodities have contributed to the price increases for food commodities and products. High energy prices affect agriculture where inputs (fertilizer, mechanization at the farm) are energy intensive. On-farm energy management has huge potential for improving the environment, lowering farm production costs, and decreasing reliance on foreign energy supplies.

Managing the impact of biofuels requires policy development across multiple stakeholders and technological innovation. The extent of competition between crops for biofuels with food production remains a significant question that needs to be addressed by a broad range of stakeholders. Advances in biotechnology can mitigate the impact of biofuels on food production. The developments may decrease or increase the pressure on land and water resources as the first generation of biofuels gives way to the second generation.

Workforce constraints are likely to affect food production and processing. In the United States, the limited supply of food scientists and technicians is likely to affect the development of the food-processing industry. In emerging economies, increasing trade and local food-processing are also expected to increase demand for food scientists and technicians. Graying of the U.S. farm workforce requires additional workers. Immigrant workers are an alternative, but resolution of certain immigration policies is required to suitably address the labor supply problem.

2.0 Emerging and future technologies and products

In this section, we analyze a range, though not an exhaustive set, of emerging and future technologies and products that are expected to shape the food industry.

Technologies that boost productivity and quality

Sustainable breeding through genomics

Improvements in animal breeding can improve the animal agriculture in cumulative and permanent ways.[123] Breeders want to improve a wide range of traits, such as product quality, welfare-related fitness traits, and disease resistance. Since many of these traits are difficult or expensive to measure, the science of genomics has become increasingly valuable as an addition to animal breeding.

Scientists are beginning to unravel how certain genes and their variants affect animal traits. Research is providing the fundamental knowledge of the genomics and epigenetics of animal health, food safety, and food-quality traits of livestock species, as well as new strategies to deliver such technologies. From these efforts, producers are likely to move animal breeding and production toward more animal-friendly, low-input systems, which deliver safe and high-quality foods that meet or exceed consumer expectations.

Genome sequence identification in beef animals

Scientific advances during the past century have led to dramatic improvements in the biological and economic efficiency of production and the quantity, quality, and safety of animal products. However, major challenges remain. Long-term research continues to focus on areas of reproductive longevity and animal well-being, adaptability to production environments, product quality, reduction of feed and energy inputs, enhancements in nutrient retention, and reduction of negative environmental impacts. Genetic mapping of beef animals is critical to these research efforts.

An integrated genetic map has been developed to help researchers assemble and annotate the bovine genome sequence.[124] The map is composed of approximately 17,000 markers from several genetic linkage and radiation hybrid maps developed around the world. This map was used in the bovine genome sequencing project as the scaffold for assigning sequence contigs to chromosomal positions. The research generated and annotated more than 1,500 full-length cDNA sequences, which are the gold standard for annotating genes on a genome. Bovine genome tools are being used to develop whole genome selection methods and further genome annotation in dairy and beef cattle. These accomplishments can greatly accelerate the discovery of DNA markers suitable for MAS and fine mapping of genes for economically important traits in cattle.

Disease resistance and managing attributes through genomics

Advances in biotechnology can lead to cutting-edge technologies in crop agriculture in the decades ahead. Plant genomics has become a rapidly developing field that is radically improving the understanding of plant biology and creating extraordinary tools to improve plant properties related to sustainable agricultural production, human and animal nutrition, and non-food uses of plant products.

Plant pests and pathogens are responsible for the loss of up to 15 percent of the world's potential food-crop yield.[125] Plant science and molecular biotechnology can solve this problem through an improved knowledge of host-pathogen interactions, the development of new diagnostic tools, and the use of genetic modification to create durably resistant crop-plant varieties.

Similarly, the transfer of disease-resistant genes is potentially an important application of biotechnology in animal production. However, few applications of these techniques exist for farm animals today, particularly because their development requires huge investments in time and money.

123 SABRE (2006) A European Integrated Research Project on Cutting Edge Genomics for Sustainable Animal Breeding. 6th Research Framework Programme of the European Union. European Commission, Directorate E03 - Security of Food Production Systems

124 United States Department of Agriculture (2007) Food Animal Production. In: National Program Annual Report: FY 2006; National Program 101, USDA, Washington, D.C.

125 European Commission (2007) Plants For the Future, 2025: A European Vision for Plant Genomics and Biotechnology. The Genval Group. Directorate-General for Research, Information and Communication Unit, B-1049 Brussels

The private sector has made selected investments in research with the intent of using transgenic farm animals as bioreactors for producing human therapeutic proteins and as organ donors for transplants in humans. Several transgenic animal products are already in various phases of clinical trials. According to some estimates, the world's demands on human pharmaceutical proteins may largely be met by transgenic farm animals in the near future.[126]

The future competitiveness of agricultural and food processing industries will depend on plant genomics, biotechnology, and their safe and reliable applications.[127] The leading-edge biotechnologies for the future are likely to be genomics and functional genomics, bioinformatics, genetic modification and transgenesis, gene expression, DNA microarrays, marker-assisted breeding, and quantitative trait loci.

Molecular marker technology in plant breeding

Molecular markers are identifiable DNA sequences that are found at specific locations in the genome and that are transmitted by the standard laws of inheritance from one generation to the next. Conventional plant breeding methods revolve around three basic steps: generation of a population of plants having desirable traits, evaluation and selection of superior individuals, and recombination of the superior individuals to generate a new population for subsequent cycles of selection and improvement.[128]

Molecular markers can help breeders evaluate and select improved new varieties. The main benefit of incorporating MAS into a traditional plant breeding program is that it increases the efficiency of the program and can speed the introduction of new varieties by reducing or eliminating costly, time-consuming field evaluation to select superior individuals.[129] Molecular markers are a powerful tool that can pinpoint genes and manipulate them directly to create new, improved varieties.[130]

Intragenic crop improvement

The intragenic approach to genetic engineering — a novel strategy developed recently — improves existing varieties by eliminating undesirable features and activating dormant traits. It transforms plants with native genetic attributes to fine-tune the activity of target genes.[131] The methods available to improve crops have their benefits and limitations.

Traditional methods can provide the baseline genetic material with important combinations of traits. Genetic engineering can be used to eliminate undesirable features while enhancing positive traits. Transgenic and xenogenic methods can be applied to introduce powerful new traits into commodity crops, whereas intragenic methods for specific crops and famigenic methods within an ecosystem may provide more cost-effective and acceptable strategies for improving specialty crops.[132] By using modern techniques to modify the genetic material used by breeders, intragenic approaches may emerge as an acceptable extension of traditional crop improvement.

The intragenic approach has already been used to enhance flavor in a potato variety by reducing amounts of the toxic compound acrylamide.[133] Potential new targets include decreasing the allergenicity and increasing the antioxidant values of crops. Since the technique uses the plant's own DNA, excludes foreign DNA transfer, and analyzes insertion events on a molecular level, intragenic plants are as safe as those developed through traditional plant breeding.[134]

Clonal seed production

Clonal seed production, or apomixis, promises to revolutionize plant breeding by providing a system for improving crops that allows any desired variety, including hybrids, to breed with uniformity. Clonal seed production is expected to improve the efficiency of breeding and seed production. Using the system, plant breeders can develop varieties that are specifically adapted to local conditions that, in turn, use (and, therefore, conserve) greater genetic diversity. Apomixis could also allow resource-poor farmers to replant the seed they produce from locally bred varieties year after year, a strategy not possible with today's commercial hybrid varieties.

The Advanced Technology Program[135] predicts that a fully embraced apomixis technology could raise the yields of most major crops by 10 percent to 50 percent annually, reducing U.S. crop production costs by more than $10 billion each year. The technology could also reduce hybrid corn

126 Yang, X., Tian, X. C., Dai, Y., and Wang, B. (2000) Transgenic Farm Animals: Applications in Agriculture and Biomedicine, Biotechnology Annual Review, Vol. 5, pg. 269-292

127 Gianessi, L. P., Silvers, C. S., Sankula, S., and Carpenter, J. E. (2002) Plant Biotechnology: Current and Potential Impact for Improving Pest Management in U.S. Agriculture: An Analysis of 40 Case Studies National Center for Food &Agricultural Policy, Washington, D.C.

128 Dreher, K., Morris, M., Khairallah, M., Ribaut, J.-M., Pandey, S., and Srinivasan, G. (2000) Is marker-assisted selection cost-effective compared to conventional plant breeding methods? The case of Quality Protein Maize. In: *Proceedings of the Economics of Agricultural Biotechnology, Ravello,* Italy, pg. 24–28, August

129 Reece, J. D., and Haribabu, E. (2007) Genes to Feed the World: The Weakest Link? Food Policy, 32 (4), pg. 459-479

130 Snape, J. W. (2004) Challenges of Integrating Conventional Breeding and Biotechnology: A Personal View! In: *New directions for a diverse planet*. Proceedings of the 4th International Crop Science Congress, 26 September–1 October, at Brisbane, Australia

131 Rommens, C. M., Haring, M. A., Swords, K., Davies, H. V., and Belknap, W.R. (2007) The intragenic approach as a new extension to traditional plant breeding, *Trends in Plant Science* 12(9), pg. 397-403

132 *Ibid.*

133 Rommens, C. (2007) Intragenic crop improvement: Combining the Benefits of Traditional Breeding and Genetic Engineering. *Journal of Agricultural and Food Chemistry* 55 (11), pg. 4281 - 4288

134 Rommens, C. (2007)

135 Advanced Technology Program (2007) Biotechnology for Conferring Apomixis (Clonal Seed Production) to Crops. *Project Brief,* Gemini Life Sciences, Inc, 5 West Center, Sugar City, ID 83448

seed production costs in the United States by 84 percent, an annual savings of nearly $366 million. Additionally, the time to market for new seed products, which usually involves 12 years of breeding and field testing, could be reduced by 60 percent or more. Apomixis is an enabling technology, proven by nature to increase productivity and efficiency, and is likely to contribute to building a more efficient agricultural industry.

Biological containment of genetically modified plants

Biological containment uses genetic modification techniques to prevent persistent cross-pollination of genetically modified crops with other plants. Biological containment systems are important in reducing the potential risk of any unintentional release of genetically modified organisms into the environment. Most molecular approaches to control gene flow among crops and weeds have so far focused on maternal inheritance, male sterility, and seed sterility.[136]

Other containment strategies may also prove useful in restricting gene flow. These include apomixis, cleistogamy (self-fertilization without opening the flower), genome incompatibility, chemical induction or deletion of transgenes, fruit-specific excision of transgenes, and transgenic mitigation (transgenes that compromise fitness in the hybrid). To date, however, no strategy has proven broadly applicable to all crop species. A combination of approaches may prove most effective for engineering the next generation of genetically modified crops.[137]

Functional transgenic crop-based foods

Micronutrient malnutrition affects more than half of the world population, particularly in developing countries.[138] Biofortification, or the delivery of micronutrients via micronutrient-dense crops, offers a cost-effective, sustainable approach to meet this challenge. Many traits needed for biofortification can be found by exploring the genetic variation in germplasm collections. Advances in nutritional genomics and efficient molecular marker techniques allow researchers to track complex traits along the breeding process. Powerful new techniques are being added to the arsenal of molecular and genomic tools, such as increasing the number of fully sequenced genomes and TILLING,[139] which is saturating metabolic pathways with mutations and subsequently identifying the genes involved.

Transgenic approaches can complement ongoing breeding efforts and provide the urgently needed biofortified crops to feed the burgeoning world population with functional and nutritious food. These include recent work on tomatoes, which boosted foliate accumulation 15-fold by tweaking a highly compartmentalized pathway,[140] and demonstrated similar developments in rice grains.[141]

High-throughput approaches to optimize nutritional value

Novel high-throughput genotyping technologies are expected to play a key role in developing large-scale analyses of plant genotypes to identify defined differences, or DNA polymorphisms, in their genetic structure.[142] The exploitation of such marker, DNA, or genome technologies in crop plants has already entered breeding programs through such concepts as 'Breeding by Design,' through which a multitude of traits can be monitored and combined.[143] However, the technology of DNA polymorphism analysis requires a quantum leap if it is to prove an effective tool for analyzing complex multigenic traits, elucidating biodiversity, and uncovering the molecular basis of adaptive traits in the genomes of wild species and domesticated crops.[144]

One example in its infancy is quantitative-trait loci (QTL) cloning. This technology, which can rapidly scan and quantify genetic traits, is likely to offer an unprecedented opportunity for understanding the genetic basis of traits, how they influence adaptation,[145] and how they might be altered to boost the nutritional value of crops and crop-based foods. This can help address the challenge of the 800 million people worldwide who are chronically malnourished, as well as the 2 billion who lack food security and others who suffer from the so-called "hidden-hunger," or micronutrient malnutrition.

Combinatorial biosynthesis to generate new natural products

Combinatorial biosynthesis is a new tool for creating novel natural products, including rare and expensive ones. The basic concept involves combining metabolic pathways in different organisms on a genetic level. As a result, heterogonous organisms provide precursors from their own primary and secondary metabolism, which are in turn metabolized to the secondary product.

136 Daniell, H. (2002) Molecular Strategies for Gene Containment in Transgenic Crops. *Nature Biotechnology*, **20**, pg. 581 - 586

137 *Ibid.*

138 Mayer, J. E., Pfeiffer, W. H., and Beyer, P. (2008) Biofortified Crops to Alleviate Micronutrient Malnutrition. *Current Opinion in Plant Biology*, 11 (2), pg. 166-170

139 Till, B. J., Cooper, J., Tai, T. H., Colowit, P., Greene, E. A., Henikoff, S., and Comai, L. (2007) Discovery of Chemically Induced Mutations in Rice By TILLING, *BMC Plant Biology*, 7, pg. 19

140 Diaz de la Garza, R. I., Gregory, III J. F., and Hanson, A. D. (2007) Folate Biofortification of Tomato Fruit, *Proceedings of the National Academy of Sciences United States of America*, 104, pg. 4218–4222

141 Storozhenko, S. et al. Folate fortification of rice by metabolic engineering, Nature Biotechnology, 25(11):1277-9

142 European Plant Science Organization (2005) European plant science: a field of opportunities. *Journal of Experimental Botany*, Vol. **56**, No. 417, pg. 1699–1709

143 Peleman, J. D. and Rouppe van der Voort, J. (2003) Breeding by design. *Trends in Plant Science*, 8, pg. 330–334

144 European Plant Science Organization (2005)

145 Ishkanian, A.S., et al. (2004) A Tiling Resolution DNA Microarray with Complete Coverage of the Human Genome. *Nature Genetics* 36, pg. 299–303

One important strategy is to identify a microbial host in which basic primary pathways can be exploited to produce biosynthetic precursors for further secondary pathways.[146] A major challenge is the gap in knowledge about genes and their regulation, particularly in key plants of interest. However, the number of genes that have been identified from biosynthetic pathways is steadily increasing, and combining different genes of different organisms has proven a viable approach.[147] This makes the realm of combinatorial biosynthesis one of the most exciting new areas for plant biotechnology.

Technologies and practices that improve the sustainable use of inputs

Renewable soil fertility replenishment technologies

Low soil fertility is one of the most important biophysical constraints to increasing agricultural productivity in sub-Saharan Africa. Several renewable soil fertility replenishment (RSFR) technologies have been developed based on nutrient recycling principles. However, the adoption of such technologies has generally lagged behind scientific advances, reducing the potential impacts of the technologies.[148]

To enhance the adoption of RSFR technologies, it is important to target the technologies to their biophysical and social niches, facilitate appropriate policy and institutional contexts for dissemination, and understand the broader context and dynamics of the adoption process. A paradigm shift may be needed in the approach to the RSFR dissemination, for example, expanding RSFR to high-value crop systems or exploring its synergy with inorganic fertilizer. Incentives may be needed to encourage farmers to acknowledge natural resource implications when making agricultural production decisions.[149]

In the foreseeable future, discussions on the development of sub-Saharan Africa will include an increasing emphasis on enhancing food production while maintaining the agricultural resource base and the resilience of the agroecosystem. RSFR technologies are likely to remain a key part of that discussion.

Increasing water efficiency of crops

The process of bio-water saving aims to increase the efficiency of a crop's water use, measured by the yield per unit of water input. This is achieved largely by exploiting the physiological and genetic potential of organisms themselves.[150] For example, plant water use efficiency is determined by photosynthesis and transpiration, both of which rely critically on stomata. Recent research on the genes regulating stomatal density and the role of stomatal density in water use may lead to increased plant water use efficiencies.[151]

Farming using salt water

The general perception throughout most of the world is that saline water in soil is detrimental to agriculture. However, historical and recent data suggest saltwater agriculture can be a viable or even desirable alternative to conventional agriculture in some situations. Such alternatives are sorely needed. Huge land areas worldwide are already salt-affected, and major regions overlie saline aquifers. While the increase in soil and water salinity in many agricultural areas of the world has created major challenges for food crop production, it has also presented some new prospects for both crop and livestock agriculture.[152]

Seawater can be used in four basic ways in agriculture.[153] Desalinization extracts salt from the water, but remains generally too expensive for widespread use in agriculture. In farming areas close to the coastline, deep and very cold seawater can be used to induce moisture from the local atmosphere. Seawater greenhouses can use sunlight to vaporize or re-precipitate seawater. Finally, seawater can be used directly for irrigation of halophyte, or salt-tolerating plant stock.

Some 10,000 halophyte plants exist today, 250 of which are potential staple crops.[154] Research is ongoing worldwide to enhance the productivity of halophytes, with the goal of creating halophilics, which thrive on high-salt water. More than 100 halophyte plants are now in trials for commercial applications.[155]

Nearly 20 countries are involved with saline farming experiments for food production. The Chinese have reported growing genomic versions of tomatoes, eggplant, pepper, wheat, rice, and rapeseed grown on beaches using

146 Julsing, M. K., et al. (2006) Combinatorial biosynthesis of medicinal plant secondary metabolites *Biomolecular Engineering*, 23 (6), pg. 265-279

147 Dejong, J. M., et al. (2006) Genetic engineering of taxol biosynthetic genes in *Saccharomyces cerevisiae*. Biotechnology and Bioengineering. 93, pg. 212–224

148 Ajayi O. C., et al. (2007) Adoption of Renewable Soil Fertility Replenishment Technologies in the Southern African Region: Lessons learnt and the way forward. *Natural Resources* Forum, Vol. 31(4) pg. 306-317

149 Ajayi, O. C. (2007) User Acceptability of Soil Fertility Management Technologies: Lessons from Farmers' Knowledge, Attitude and Practices in Southern Africa. Journal of Sustainable Agriculture 30(3): pg. 21–40

150 Shi, Y. C.(1999) Way of exploitation: Biological water saving. *Science and Technology* Review, **10**, 3–5

151 Wang, Y, Chen, X., Xiang, C. B. (2007) Stomatal density and bio-water saving. *Journal of Integrative. Plant Biology*. **49**(10), 1435–1444.

152 Masters, D. G., Benes, S. E., and Norman, H. C. (2007) Biosaline agriculture for forage and livestock production. *Agriculture, Ecosystems & Environment*, **119**(3-4), Pages 234-248

153 Omar, S.A. (2003) Agricultural Bio-Saline Research and Development in Kuwait. In: *ISHS Acta Horticulturae* **609**: International Symposium on Managing Greenhouse Crops in Saline Environment

154 Bushnell, D. (2005) Seawater/Saline Agriculture for Energy, Warming, Water, Rainfall, Land, Food and Minerals. NASA Langley Research Center

155 *Ibid.*

seawater.[156] The outlook for genomic-derived halophyte enhancements appears to be quite favorable, considering the substantial improvements thus far and the fact that research is still in the early stages regarding enhanced growth rates, reduced water and nutrient requirements, and ways to optimize plants for specific biorefining processes.[157]

Novel water purification technologies

Next-generation purification systems include novel methods to disinfect water without intensive use of chemicals or the production of toxic byproducts. These techniques sense, transform, and remove low-concentration contaminants even in high backgrounds of potable constituents — using, for instance, photons and engineered nanostructures or microorganism-based water purification technologies. Other methods involve reusing wastewater and desalinating water from sea and inland saline aquifers. These technologies hold great promise for effectively increasing water supplies.[158]

Technologies that improve the health and wellness attributes of food

Food as a vehicle for drug or biologic delivery

Particulate drug delivery systems have been used in clinical and experimental therapeutics in a range of applications targeting different disease states. Their popularity is partly due to the ease in administering the suspensions or dry powders through food. Depending on the type of particle, the delivery systems can also be relatively easy to manufacture. The size of the particles plays a substantial role in determining the properties of the final product and its potential applications.

Formulations developed for medicine and experimental pharmaceutics are intended for a relatively low-volume, high-margin market. By contrast, the food industry is high volume, low margin. That difference presents a challenge for manufacturers. Pharmaceutical companies generally use complex processes and expensive ingredients, such as polymers. However, such formulations would significantly strain the business plan for most food products.[159]

Regulatory issues can present challenges. Approval of a material for a drug delivery system does not mean that it will be approved for use in food. The barriers and conditions encountered by systemic drug delivery systems differ from those to which foods are exposed.[160] However, given that consumers are likely to embrace food as a vehicle for drug delivery, this technology holds promise for widespread use in the future.

Microencapsulation in food

Preparing high-quality, nutritious food depends greatly on the availability of effective delivery systems for nutrients. Such systems should preserve the specific nutritional, biological, chemical, and functional properties of the food's most sensitive constituents and should effectively release those after ingestion.[161] Current technologies for delivering such nutrients and ingredients fall short of meeting these goals. There is a strong need for new, highly functional delivery systems. The most promising technology is microencapsulation, which involves the entrapment and controlled delivery of biologically active or sensitive components.

Microencapsulation has been used successfully for drug delivery for several decades, but its use in food is still quite new and is composed of a limited array of workable GRAS encapsulating agents and technologies.[162] It is likely that microencapsulation will be a leading food technology in the near future to deliver nutrients through food.

Molecular docking to predict enzyme functioning

Molecular docking is an optimization task aimed at minimizing the intermolecular interaction energy between two molecules to find the best protein-ligand complex geometry.[163] A binding interaction between a small molecule ligand and an enzyme protein may activate or inhibit the enzyme. If the protein is a receptor, ligand binding may result in agonism or antagonism.[164]

Docking is most commonly used in the field of drug design.[165] Most drugs are small organic molecules, and docking may be applied to:

- Hit identification in which docking is combined with a scoring function to quickly screen large databases of potential drugs in silico to identify molecules that are likely to bind to a particular protein.
- Lead optimization in which docking can be used to predict the location and relative orientation of a ligand's bond to a protein.

156 *Ibid.*

157 Ahmad, R., and Malik, K. A. (2002) "Prospects for Saline Agriculture" *Tasks for Vegetation Science* Vol. 37, Kluwer Academic Publishers

158 Shannon M. A., et al. (2007) Science and Technology for Water Purification in the Coming Decades. *Nature* 452, pg. 301-310

159 Kohane, D. S. (2007) Micro- and Nanoparticles for Drug Delivery. *The World of Science*. Copyright 2007, IFT and IUFoST

160 Kohane, D. S, et al. (2006) Biodegradable Polymeric Microspheres and Nanospheres for Drug Delivery in the Peritoneum. *Journal of Biomedical Materials Research*, 77A (2), Pages 351 - 361

161 Rosenberg, M., and Lee, S-J. (2004) Water-insoluble. Whey Protein-Based Microspheres Prepared by an All-Aqueous Process. *Journal of Food Science*., **69**(1): FEP51-FEP57

162 Rosenberg, M. and Lee, S. J. (2004) Calcium-Alginate Coated, Whey Protein-Based Microspheres: Preparation, Some Properties and Opportunities. *Journal of Microencapsulation*. **21**(3), pg. 263-281

163 Bikadi, Z., Kovacs, S., Demko, L., and Hazai, E. (2008) DockingServer. *Virtua Drug Ltd.*, Budapest, Hungary, www.dockingserver.com. Retrieved on September 3, 2008.

164 Kahraman, A., et al. (2007) "Shape Variation in Protein Binding Pockets and Their Ligands". Journal of. *Molecular Biology*, 368 (1): pg. 283–301

165 Kitchen, D. B., Decornez, H., Furr, J. R., and Bajorath, J. (2004) "Docking and Scoring in Virtual Screening for Drug Discovery: Methods and Applications." *Nature Reviews Drug Discovery* 3 (11): pg. 935–49

Molecular docking in enzymology has significant potential as a way to deliver drugs or biologics through food.

Nutrigenomics to customize diets

Nutrigenomics is an interdisciplinary science that combines elements of genomics, molecular biology, clinical research, nutritional science, and phyto-biotechnology in the search for new strategies to personalize the prevention and treatment of nutrition-related diseases.[166] Research findings on the interrelationship between nutrition and the human genome are creating commercial applications both for producing food and for preventing diet-related diseases through, for instance, diagnostic tools.

Global research activities now range in scope from fundamental research to the development of market-ready products and services. These activities include techniques and strategies to:

- diagnose metabolic diseases;
- identify and analyze genetic factors related to obesity;
- conduct metabolic and genetic profiling;
- identify natural substances to prevent and treat cancer and Syndrome X, known as metabolic syndrome;
- develop other innovative treatments for Syndrome X;
- develop new strategies and products to treat adipositas;
- explore the genetics and pharmacogenomics of obesity;
- develop an in-silico disease model for type 2 diabetes;
- apply nanowell PCR for gene expression;
- develop a profile analysis related to cardiovascular diseases;
- create a quick-test system based on a DNA microarray to detect food-borne allergens;
- profile allergens;
- create screening systems to detect colon cancer in its early stages;
- develop an EGF inhibitor test system for treating colon cancer;
- explore tumor-prophylactic food additives;
- identify new diagnostic markers for celiac disease;
- detect immune-reactive components in foodstuffs;
- develop C5a receptor antagonists as a new treatment for Crohn's disease;
- develop DNA adducts to assess the safety of conventional and novel foods; and
- use humanized mouse models for enzymes that metabolize exogenous substances.

166 Kompetenznetze (2006) Networks of Competence in Germany. Federal Ministry of Economics and Technology. Arabellastr. 17, D-81925, Munich www.kompetenznetze.de. Retrieved on September 30, 2008.

Food processing technologies

Nanotechnology for food applications

Nanotechnology allows designers to alter the structure of packaging materials on the molecular scale to give the materials desired properties. Traditional packaging is likely to be replaced with multifunctional intelligent packaging methods that improve food quality through nanotechnology applications. For example, nanoparticles of silver, magnesium oxide, or zinc oxide can be used to create antimicrobial food packages, which kill harmful microorganisms. Nanosensors on food packages could be used to detect chemicals, pathogens, and toxins in foods.[167] Food packages with dirt-repellant coatings are also being developed using incremental layering of nanoparticles. In addition, nanowheels, nanofibers, and nanotubes are being studied as ways to improve the properties of food packages.[168]

Nanobiotechnology can significantly impact the food and food-processing industries, allowing improvements in the fundamental characteristics of food packaging materials, such as strength, barrier properties, antimicrobial properties, and stability to heat and cold. In 2005, more than 180 applications were in different stages of development, with a few already in the market.[169]

According to one study, the nanofood market is predicted to grow significantly within the next few years, from $2.6 billion to an estimated $20.4 billion by 2010. According to another estimate, the market for nanotechnology in food packaging alone is expected be around $360 million in 2008.[170] In large part, the impetus for this predicted growth is the extraordinary benefit that nanoscience offers to improve food packages. More than 200 companies around the world are now active in research and development in this area.[171] The United States is the leader, followed by Japan and China. Asia, with more than 50 percent of the world's population, is expected to be the largest market for nanofood by 2010.

167 Kuzma, J., and VerHage, P. (2006) Nanotechnology in Agriculture and Food Production: Anticipated Applications. *Project on Emerging Nanotechnologies*, Woodrow Wilson International Center for Scholars September 2006

168 Mc Hugh, T. H. (2008) Food Nanotechnology - Food Packaging Applications. *The World of Food Science*. Vol **4**, pg. 1-3

169 Asadi, G., and Mousavi, M. (2006) Application of Nanotechnology in Food Packaging. *13th World Congress of Food Science & Technology*, IUFoST.

170 Mc Hugh, T. H. (2008) Food Nanotechnology - Food Packaging Applications. *The World of Food Science*. Vol **4**, pg. 1-3

171 Moraru, C., Panchapakesan, C., Huang, Q., and Takhistov, P.(2003) Nanotechnology: A new frontier in food science. *Food Technology*,**57**, pg. 25-27

Green chemistry applications in packaging

Green chemistry is the design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances.[172] Novel and advanced polymeric materials based on green chemistry are being developed to enhance food packaging. Work in this area uses conventional polymer science methods, as well as newer technologies, such as biopolymers, nanotechnology, and nanocomposites, to create active, intelligent packaging. Bio-based materials, in conjunction with nanotechnology, are expected to spur a major breakthrough in the plastic packaging industries. Such materials, including polymeric blends, composites, and nanocomposites, are likely to find niche applications in both the flexible and rigid packaging sectors. [173]

There is a growing urgency to develop and commercialize natural, resource-based materials and innovative technologies for packaging. New material development is moving from petroleum-based chemistry to green chemistry, driven by unstable petroleum prices, as well as growing environmental and national security concerns. The switch to a bio-based economy can challenge agriculture, forestry, academia, government, and industry. The future of food packaging is expected to be sustainable if it is developed through innovative, synergistic research approaches.[174] Green polymers, such as polylactic acid, polyhydroxyalkanoates, starch plastics, and bio-based polytrimethylene terephthalate, show potential in greening the packaging industry. [175]

Microbial transformation for producing natural flavors

Microbial transformation, which alters flavors by the addition of specific microorganisms, has emerged as an important approach for producing natural flavors in high quantities. Because such biotransformation processes are environmentally friendly and the products are considered "natural," the method is attracting more attention from food producers and, in some cases, consumers.

Flavors and fragrances are widely used in the food, beverage, and cosmetic industries. In 2006, they represented a worldwide market of $18 billion per year, which is projected to grow steadily.[176] Today, most flavors are created by chemical synthesis. Less than 5 percent are extracted from plants and can, therefore, be classified as natural. Under FDA and European regulations, products obtained by biotechnological methods are natural if the substrate for the process is of natural origin.[177]

Future research is likely to focus on characterizing the metabolic process and on optimizing the biotransformation to improve the yields of target products from the laboratory to industrial use.[178]

Food safety and supply chain management technologies

Information systems to manage supply chains

The dynamic configuration of long food supply chains needs more research attention.[179] Networked food manufacturing enterprises are likely to undergo significant paradigm shifts and technological advancements as they adjust to opportunities and threats emerging from increased global trade and other market trends.[180] The future in information systems to monitor food supply chains is expected to include the wide acceptance of advanced, high-speed information and communication technologies through partnering with companies or outsourcing services. In particular, these virtual enterprises and collaborative work environments are likely to include technologies that share design product development information through the product's life cycle, which will help subcontractors assess a design's feasibility before purchase.

Non-thermal food processing

Non-thermal processing methods interest food scientists, manufacturers, and consumers because they extend shelf life by inhibiting or killing microorganisms, but with minimal impact on the nutritional and sensory properties of foods. Non-thermal food preservation processes are considered to be more energy efficient and to better preserve food quality than conventional processes.[181] Non-thermal processes also meet industry needs by offering value-added products, new market opportunities, and added safety margins.

Several non-thermal processing methods and technologies are currently available or in development to deactivate microorganisms, extend microbiological shelf life in foods,

172 Anastas, P., and Warner, J. (1998) Green Chemistry: Theory and Practice (Oxford University Press: New York, 1998)

173 Manias, E. (2006) "Polymer/Inorganic Nanocomposites: Opportunities for Food Packaging Applications" In: Food Packaging Innovations: The Science, Current Research and Future Research Needs. *Proceedings of IFT Food Summit, May 7-9, 2006, Baltimore, MD*

174 Mohanty, A. K. (2006) "Bio-based Materials for a Sustainable Future in Packaging", In: Food Packaging Innovations: The Science, Current Research and Future Research Needs. *Proceedings of IFT Food Summit*, May 7-9, 2006, Baltimore, MD

175 Srienc, F. (2008) Green Chemistry at the BioTechnology Institute. In: S. Kelley and R. M. Yawson (eds.) "Opportunities and Challenges for Leadership" *Proceedings of the 1st Green Chemistry Conference in Minnesota,* May 28, 2008, Minneapolis, MN

176 Leffingwell & Associates (2008) 2003 - 2007 Flavor & Fragrance Industry Leaders http://www.leffingwell.com/top_10.htm. Retrieved on September 10, 2008.

177 Serra, S. et al. (2005) Biocatalytic preparation of natural flavours and fragrances. *Trends in Biotechnology*. 23, pg. 193–198

178 Xu, P., Hua, D., and Ma, C. (2007) Microbial Transformation of Propenylbenzenes for Natural Flavor Production. *Trends in Biotechnology*. 25 (12), pg. 571-576

179 Jain, V., Wadhwa, S., and Deshmukh, S. G. (2007) "A Negotiation-to-Coordinate (N2C) Mechanism for Modeling Buyer-Supplier Relationship in Dynamic Environment", *International Journal of Enterprise Information Systems*, Vol. 3 No.2, pg.1-27

180 Jain, V., and Benyoucef, L. (2007) Managing Long Supply Chain Networks: Some Emerging Issues and Challenges. *Journal of Manufacturing Technology Management*, Vol. 19 No. 4, pg. 469-496

181 Ortegas-Rivas, E., Rodriguez, E. Z., and Barbosa-Canovas, G. V. (2005) Preserving Quality Attributes of Apple Juice by Means of Non-Thermal Preservation techniques.http://www.msstate.edu/org/fsfa/abstracts98.htm. Retrieved on September 9, 2008.

and identify packaging interactions that might result in unsafe food. Those techniques include ultra-high-pressure techniques, ionizing radiation, such as pulsed x -ray, ultrasound, pulsed light and pulsed electric fields, high-voltage arc discharge, magnetic fields, dense phase carbon dioxide, and hurdle technologies.[182, 183]

Real-time sensing of pathogens

The need for real-time monitoring in the modern, highly automated food processing environment has stimulated research into rapid microbiological testing. Despite these detailed studies, the food industry still demands new techniques and technologies to accurately and rapidly assess microbial spoilage in foods, real time and without destroying the food itself.

Current detection methods are expected to be replaced by those that detect microbial spoilage in meats within seconds as opposed to hours. Among the key reasons for this optimism are the continuous advances in analytical instrumentation, progress in miniaturization of those instruments, the increasing speed of computer processing, and better tools for more complex data analysis.

Biosensors for rapid detection of viruses

New biosensor technologies are being developed to identify pathogens in clinical, food, and environmental samples. One example is the Ibis T5000, which couples nucleic acid amplification with high-performance electrospray ionization mass spectrometry and base-composition analysis.[184] The system not only detects virulence factors and antibiotic resistance markers, but also identifies and quantifies a broad set of pathogens, including all known bacteria, all major groups of pathogenic fungi, and the major families of viruses that cause disease in humans and animals.

Technologies to screen for multiple chemical contaminants

Monitoring for chemical contaminants in foodstuffs is critical for maintaining and improving food quality and safety, but it is also complex and time consuming. Rapid and efficient transcriptomics, proteomics, and biosensor-based technologies are being developed and are likely to improve the task of screening for chemical contaminants. These new systems would be able to detect pesticides (organochlorines and stobilurins), heavy metals (lead, mercury, etc.), natural toxins produced by shellfish (paralytic shellfish poisons), fungi and moulds (trichothecenes and mycotoxins), therapeutic drugs (hormonal growth promoters and quinolone antimicrobials), and endocrine disrupters (phytoestrogens).[185]

Summary

In this section, we explored emerging and future technologies and products. The findings are summarized below:

- technologies that improve the productivity of agricultural systems and animal production;
- technologies and practices that improve the sustainable use of inputs;
- technologies that improve the health and wellness qualities of food;
- food processing technologies; and
- food safety and supply chain management technologies.

Technologies that boost productivity and quality

Sustainable breeding through genomics: Current research is providing the fundamental knowledge of the genomics and epigenetics of animal health, food safety, and food quality traits of livestock species, as well as new strategies to deliver such technologies.

Genome sequence identification in beef animals: An integrated genetic map has been developed to help researchers assemble and annotate the bovine genome sequence. These accomplishments greatly accelerate the discovery of DNA markers suitable for MAS and fine mapping of genes for economically important traits in cattle.

Disease resistance and managing attributes through genomics: The leading-edge biotechnologies to influence the future of food and animal production are expected to be genomics and functional genomics, bioinformatics, genetic modification and transgenesis, gene expression, DNA microarrays, marker-assisted breeding, and quantitative trait loci.

Molecular marker technology in plant breeding: Molecular markers are a powerful tool that can pinpoint genes and manipulate them directly to create new, improved varieties.

Intragenic crop improvement: The intragenic approach to genetic engineering can improve existing varieties by eliminating undesirable features and activating dormant traits.

182 Morris, C., Brody, A. L., and Wicker, L. (2007) Non-Thermal Food Processing/Preservation Technologies: A Review with Packaging Implications. *Packaging Technology and Science*, 20(4), pg. 275-286

183 Considine, K. M., et al. (2008) *FEMS Microbiology Letters* 281(1): pg. 1 - 9

184 Ecker, D. J. et al. (2008) Ibis T5000: A Universal Biosensor Approach for Microbiology. *Nature Reviews Microbiology*, 6, pg. 553-558

185 BioCop (2007) New Technologies to Screen Multiple Chemical Contaminants in Foods. An Integrated Project Funded by the European Commission under the Food Quality and Safety Priority Thematic Area. Contract Number: FOOD-CT-2005-006988

Clonal seed production: Clonal seed production, or apomixis, promises to revolutionize plant breeding by providing a system for improving crops that allows any desired variety, including hybrids, to breed with uniformity.

Biological containment of genetically modified plants: Biological containment systems are important to reduce the potential risk of any unintentional release of genetically modified organisms into the environment.

Functional transgenic crop-based foods: Transgenic approaches can complement ongoing breeding efforts and provide the urgently needed biofortified crops to feed the burgeoning world population with functional and nutritious food.

High-throughput approaches to optimize nutritional value: Novel high-throughput genotyping technologies are expected to play a key role in developing large-scale analyses of plant genotypes to identify defined differences, or DNA polymorphisms, in their genetic structure.

Combinatorial biosynthesis to generate new natural products: Combinatorial biosynthesis is a tool that can create natural, rare, and expensive products. The basic concept involves combining metabolic pathways in different organisms on a genetic level.

Technologies and practices that improve the sustainable use of inputs

Renewable soil fertility replenishment technologies: Low soil fertility is one of the most important biophysical constraints to increasing agricultural productivity in sub-Saharan Africa. In the foreseeable future, discussions on the development of sub-Saharan Africa will increasingly focus on the need to enhance food production while maintaining the agricultural resource base and the resilience of the agroecosystem. RSFR technologies are likely to remain a key part of that discussion.

Increasing water efficiency of crops: Recent research may lead to increased plant water use efficiencies through genetically manipulating stomatal density.

Farming using salt water: Seawater can be used in four basic ways in agriculture. Desalinization extracts salt from the water, but remains generally too expensive for widespread use in agriculture. In farming areas close to the coastline, deep and very cold seawater can be used to induce moisture from the local atmosphere. Seawater greenhouses can use sunlight to vaporize or re-precipitate seawater. Finally, seawater can be directly used for irrigation of halophyte, or salt-tolerating, plant stock. The outlook for genomic-derived halophyte enhancements appears to be quite favorable.

Novel water purification technologies: Next-generation purification systems include novel methods to disinfect water without intensive use of chemicals or the production of toxic byproducts. These techniques sense, transform, and remove low-concentration contaminants even in high backgrounds of potable constituents — using, for instance, photons and engineered nanostructures or microorganism-based water purification technologies.

Technologies that improve the health and wellness attributes of food

Food as a vehicle for drug or biologic delivery: Particulate drug delivery systems have become widely used in clinical and experimental therapeutics in a range of applications targeting different disease states. Considering many consumers will embrace food as a vehicle for drug delivery, it is likely that the technology will become widespread in the future.

Microencapsulation in food: Microencapsulation has been used successfully for drug delivery for several decades, but its use in food is still quite new and is comprised of a limited array of workable GRAS encapsulating agents and technologies.

Molecular docking to predict enzyme functioning: Molecular docking in enzymology has huge potential for food technology as a way to deliver drugs or biologics.

Nutrigenomics to customize diets: Research findings on the interrelationship between nutrition and the human genome are creating commercial applications both for producing food and for preventing diet-related diseases through, for instance, diagnostic tools.

Food processing technologies

Nanotechnology for food applications: Nanotechnology allows designers to alter the structure of packaging materials on the molecular scale to give the materials desired properties.

Green chemistry applications in packaging: Novel and advanced polymeric materials based on green chemistry are being developed to enhance food packaging. Work in this area uses conventional polymer science methods, as well as newer technologies, including biopolymers, nanotechnology, and nanocomposites, to create active, intelligent packaging.

Microbial transformation for producing natural flavors: Microbial transformation, which alters flavors by the addition of specific microorganisms, has emerged as an important approach for producing natural flavors in high quantities.

Food safety and supply chain management technologies

Information systems to manage food supply chains: The dynamic and longer food supply chains need more research attention. The future in information systems to monitor food supply chains is expected to include the wide acceptance of advanced, high-speed information and communication technologies through partnering with companies or outsourcing services.

Non-thermal food processing: Several non-thermal processing methods and technologies are currently available or in development to deactivate microorganisms, extend microbiological shelf life in foods, and identify packaging interactions that might result in unsafe food. Those techniques include ultra-high-pressure techniques, ionizing radiation, such as pulsed x-ray, ultrasound, pulsed light and pulsed electric fields, high-voltage arc discharge, magnetic fields, dense phase carbon dioxide, and hurdle technologies.

Real-time sensing of pathogens: The need for real-time monitoring in the modern, highly automated food processing environment has stimulated research into rapid microbiological testing that can detect microbial spoilage in meats within seconds as opposed to hours. This can be developed based on advances in analytical instrumentation, progress in miniaturization of those instruments, the increasing speed of computer processing, and better tools for more complex data analysis.

Biosensors for rapid detection of viruses: New biosensor technologies are being developed to identify pathogens in clinical, food, and environmental samples.

Technologies to screen for multiple chemical contaminants: Rapid and efficient transcriptomics, proteomics, and biosensor-based technologies are being developed and are expected to improve the task of screening for chemical contaminants.

The trends and technologies discussed in the first two sections present potential opportunities in the industry. As we have mentioned, this is not *the* universal set of opportunities. It is *a* set of opportunities that emerged from our rigorous process. It is important to note that these opportunities are expected to vary with time and new knowledge. Because of our process, however, we are confident that a range of technologies and products presented here represent the direction of product development and technological innovation in the food industry.

3.0 Exploring possible futures and identifying opportunities

The breadth of trends and technologies present an uncertain landscape for decision makers entrusted with strategic planning. Given the time horizon and uncertainties in predicting the future accurately, these decision makers face strategic risks.

In this section, we apply a framework to assist decision making in the face of uncertainty and to identify opportunities in the food industry.

In industry, a chief executive officer would like to predict which market segments are likely to grow at above-average rates so that she can reconfigure the existing product mix or embark on research and development investments to create products to meet future needs. A researcher in industry would like to understand future market trends and technologies to effectively and efficiently manage her research portfolio and develop new products.

An academic involved in primary research would like to know how basic research and technologies coming out of her laboratory can be applied to develop products that respond to emerging market trends.

Policymakers in government are entrusted with a more complex and broader set of objectives. Government, as an agent of its citizens,[186] is responsible for enacting policies, developing and implementing programs, defining priorities, and allocating resources. It manages economic development, protects the environment and natural resources, invests in education to develop citizens and a competitive workforce, facilitates the provision of clean, reliable, cheap sources of energy, and oversees the public safety and health of its citizens, to name a few areas.

There are several components of public policy that influence any given industry. In the food industry, public policies influence the price and availability of food crops. Education policy allocates resources to public education systems and influences the development of a workforce with qualified food scientists, nutritionists, agricultural scientists, researchers in academia and industry, and technically qualified workers. Economic and fiscal policies influence the economic viability of regions to develop a labor force and create new businesses and new products. Energy policy affects the cost of food through the cost of fertilizers, fuel to run farm machinery, and substitution of agricultural commodities away from food to biofuels. Environmental regulation affects the location and costs of food production. Trade and safety regulations define the health and safety standards for food products. In industrialized economies, immigration policy determines the legality and availability of imported labor for food and animal production. Debate on the ethics of technologies can influence public policy to ban the technology or adopt it. Policymakers need to know where the world is headed and how can they tailor policies to serve its citizens.

The decision makers identified above often face strategic uncertainty. Constraints can limit their responses. These can be resource constraints of money, time, and human resources; structural constraints on the scope and scale of resource allocations; and strategic constraints on which services or products an entity can provide and the risks decision makers must take in the process.

Decision makers need a framework that allows them to maneuver in an uncertain environment within these constraints and to make decisions that can prepare their institutions for the future. We now proceed to describe such a framework.

Strategic flexibility framework

The Strategic Flexibility Framework has been applied in this section to explore the future of the food industry.[187] The Strategic Flexibility Framework is based on the idea that decision makers require flexibility to adjust decisions within given constraints. Strategic uncertainty requires strategic flexibility, the ability to change strategies.

Decision makers risk arbitrarily narrowing their options if they attempt to predict the future too precisely. This could prevent them from considering a broader range of possibilities. Decision makers need a range of possibilities and corresponding strategy choices, rather than one strategy based on a declared vision of the future.

186 While government is an agent of the citizens, in most cases sole accountability to citizens is influenced by other stakeholders as well. Segments of consumers, businesses, and foreign stakeholders all influence the government and its actions.

187 The Strategic Flexibility Framework has been developed by Michael Raynor of Deloitte LLP. This discussion on the framework draws from the discussion on pages 177 - 258 of "The Strategy Paradox" by Michael Raynor.

The Strategic Flexibility Framework is based on two core constructs: scenario-based planning and real options. Scenario-based planning creates potential future conditions and aims to anticipate the future rather than predict it. Options for alternative strategies are also explored, either for alternative scenarios or for a given scenario, which provides the ability to change strategies.

Scenario building allows decision makers to consider alternative, often contradictory world views, of the future. Scenario building provides an efficient way to summarize and synthesize the complex interactions between relevant variables into one world view. A scenario is a specific, relevant description of a future condition that includes key variables clustered into dimensions of uncertainty, which we call drivers.

Scenarios capture variation along several dimensions. Each scenario is a "corner solution" in the multi-dimensional space. "Interior solutions" based on interactions among all dimensions are not considered because they do not help in determining the necessary range of scenarios and strategies. Scenarios help to create strategic flexibility by envisioning the extreme cases for which a decision maker must prepare.

The next step is to determine strategies that could be successful under these scenarios. These alternative strategies generate strategic flexibility for the decision maker.

The Strategic Flexibility Framework consists of four components:

Anticipate: The unpredictability of the future presents strategic risk that cannot be managed through improved prediction. Using scenarios to define the "possibility space" over a time horizon or period creates a framework for analyzing the future without a necessarily correct prediction.

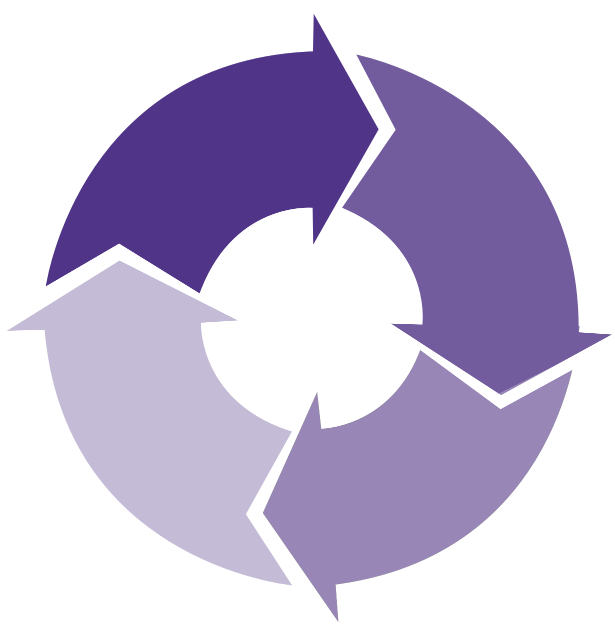
Formulate: For given scenarios, this step determines the strategies for success under different conditions. Each scenario has an optimal strategy. Each optimal strategy consists of various constituent elements — technologies, capabilities, and assets — required to execute the strategy. Elements common to many optimal strategies (one derived from each scenario) are core elements; those common to a few or one optimal strategy are called contingent elements.

Accumulate: Core elements have little strategic risk because they are part of the optimal strategies for multiple scenarios. Contingent elements require an options-based approach, which gives choices for allocating resources. In the accumulation phase, the decision maker commits to core elements and takes options on contingent elements.

Operate: This step involves monitoring the environment to determine which scenario accurately captures the most important elements of the future. This involves choosing the most appropriate optimal strategy, determining the necessary contingent elements, and deciding which options to exercise or abandon. The set of scenarios must be reviewed and, if needed, refreshed, or redeveloped.

The Strategic Flexibility Framework is described in Figure 4.

Figure 4: The Strategic Flexibility Framework



1. **Anticipate**
   Build scenarios of the future
   - Identify drivers of change
   - Define a range of possible futures
   - Determine which are truly plausible

2. **Formulate**
   Create effective strategies for each of those futures
   - Develop an optimal strategy for each scenario
   - Compare optimal strategies to define "core" and "contingent" elements

3. **Accumulate**
   Determine strategic options required
   - Commit to the core elements
   - Take options on the contingent elements

4. **Operate**
   Manage the portfolio of options
   - Monitor the environment
   - Determine which optimal strategy is most appropriate
   - Exercise relevant options
   - Combine with core elements

Source: Michael Raynor, The Strategy Paradox: Why Committing to Success Leads to Failure (and What to Do About It), Doubleday Publishing, 2007.

Applying strategic flexibility for multiple decision makers in regional industries

Traditionally, the Strategic Flexibility Framework is applied to inform a single economic entity to address a specific strategic issue. For example, it could help a food and beverage company make a strategic decision to enter a specific market. Here, the strategic decision is identified (market entry), the decision maker is unique (food and beverage company), and its capabilities, technologies, and assets are defined.

In this analysis, we are not applying the Strategic Flexibility Framework to a specific institution with defined capabilities, technologies, and assets, and therefore, defined constraints. Instead, we are applying it to inform decision makers from a generic set of academic, industrial, and governmental institutions, which we collectively referred to as "regional industry."

This application to a broad spectrum of decision makers from many regional industries requires us to customize the Strategic Flexibility Framework. We are dropping the constraints as typically used in the process and exploring the entire range of possibilities from which any institution may choose. Consequently, we cannot identify core or contingent strategies. Instead, we move this construct to a higher level — to identify a portfolio of technologies and products. We also identify knowledge clusters that need investment to competitively build a product portfolio for the regional market.

The unconstrained exploration of technologies and products allows us to identify a range of opportunities for the array of stakeholders. This would not have been possible if we had applied constraints. Applying the framework at the higher level allows the community of stakeholders to use this strategic level of insight to determine their own core and contingent strategies and tactical implementation plans.

In the first step of the framework, we identify drivers of change and develop scenarios that represent possible futures based on these drivers. We then use these to explore potential future conditions of the industry. In the second step, we identify a portfolio of technologies and products applicable across scenarios, in the absence of specific constraints. We also identify knowledge clusters required to develop these products and technologies.

Drivers of change

In this section, we identify the drivers of change that are likely to influence the food industry over the next 20 years. These drivers of change are clusters of trends and technologies discussed previously in the paper.

Science and technology

There is tremendous potential to develop nascent disciplines, technologies, processes, and food products based on advances in various "omics." Basic and applied research in biotechnology fields, such as plant and animal genomics, proteomics, systems biology, and molecular techniques, have potential to transform agriculture and food production. Technologies, such as non-thermal sterilization and nanosensors and biosensors for monitoring food quality and safety, are expected to make food processing more reliable and efficient. Additional technologies, such as online and rapid tests, are expected to improve food safety and supply chain integrity in a world of expanding trade in processed foods.

As the global population involved in farming and animal production declines due to aging and urbanization, land and water resources are increasingly diverted to non-agricultural applications, and demand for food rises with population growth and economic development, demand will grow for products and technologies that improve the productivity of agricultural and animal production. Products likely to emerge include nutraceuticals, prebiotics, probiotics, new vaccines, including potentially plant-derived therapeutics, DNA-based products, transgenic products to alter animal and food production, disease diagnostics, and screening and testing kits for food and animal production safety.

Demography

The graying of the population in the United States and other industrialized economies is likely to reduce the workforce involved in food and animal production. As the average size of animal production units expands, the multiplier effect of a retiring work force on animal production is likely to be significant. As farms continue to consolidate, scale will become increasingly important to compete effectively.

Increasing industrialization in emerging economies is accelerating the rural-to-urban transition. However, the relatively low level of mechanization in farming and animal production in emerging economies is likely to create significant opportunities for technology-based productivity improvements. In the short run, these productivity improvements may compensate for or exceed the potential loss in animal and food crop production caused by rural-to-urban transition. In the long run, sustained rural-to-urban migration coupled with the graying of the population in industrialized economies may accelerate demand for skilled workforce in food and animal production sectors.

Talent shortages of food scientists, food safety technicians, nutrition researchers, agricultural scientists, animal veterinarians, veterinary technicians, and clinical laboratory technicians are likely to affect the food industry in the United States. In emerging economies, a shortage of well-established food production and processing infrastructure and food processing professionals is likely to increase demand for these professionals.

In the United States, immigrants account for a growing share of farm and animal production workforce. Immigration policy that limits the import of skilled labor is likely to lower farm and animal production.

Energy, commodity, and input Prices

High energy and commodity prices have raised the cost of feedstock for animal production and food crops due to increases in farm inputs (e.g., fertilizer). Diversion of significant volumes of biomass away from the farm and into biofuel production also has increased the cost of animal feed and food crops.

Animal production and food crops globally are facing increasing competition for land and water resources from expanding urban and industrial use. Stagnation or low growth in livestock headcount coupled with higher feedstock costs increases livestock prices. As livestock values climb, spending to protect this more valuable asset is likely to rise.

In times of high fuel prices, consumers may become increasingly concerned about "food miles" and receptive to self-sufficient regional food supply clusters. In a world that measures and monetizes carbon emissions, fuel prices may increase to reflect the cost of these negative externalities.

Policies, standards, and regulations

Policies, standards, and regulations are significant and often unpredictable drivers of change in the marketplace. In the food industry, these drivers come in three varieties.

Food safety and health regulations determine the level of safety oversight, production and processing standards, guidelines about residues and chemical additives, leading practices at the workplace, health and nutrition labeling requirements, and guidelines on agricultural and animal production.

Trade policies and standards affect the flow of goods across geographical regions. These include tariffs and import duties that regulate trade flow by raising import prices. Standards and regulations affecting food exporters, including non-traditional barriers to trade, can reduce the flow of goods.

Environmental regulations governing animal production facilities, and odor and waste management affect food production. Policies regarding the carbon footprint of food and animal production are likely to become more prevalent. New standards for sustainable practices may lead to mandatory product labels that specify a product's carbon footprint or consumption of sustainable natural resource use.

Economy and trade

Economic shifts affect food production and availability. Strong economic growth raises demand for food products, particularly processed foods, and for higher quality and variety of food products. Strong growth in emerging economies has increased both incomes and demand for a richer diet with a higher proportion of animal protein and dairy products. As emerging economies grow, demand for animal and food products also is likely to rise. Moreover, as these emerging economies urbanize and industrialize, the need for an advanced food infrastructure is likely to increase. Local resource constraints, however, may accelerate imports from food-surplus regions.

In the livestock sector, the increasing scale and adaptation of animal production practices in emerging economies are also likely to increase supply and demand for local food products. Increasing trade in processed food products will increase demand for testing and surveillance products, as well as food safety professionals. Expanding animal and food product exports from emerging economies may tighten health and safety regulations applied to international trade. Trade policies and standards directly influence demand for animal products and the use or disuse of food products. These can be used as technical barriers to trade.

Climate and the environment

Changes in the environment are likely to alter crop production and disease emergence patterns and management in animals. Environmental changes caused by environmental degradation, human and animal demography, farming densities and practices, and climatic changes are likely to affect water availability and timing, soil quality, and zoonotic diseases.

Changes in regional climate patterns caused by long-term global warming could affect the geographic range of many infectious diseases. Another important but highly uncertain risk of climate change is its potential impact on the evolution and emergence of infectious disease agents. Ecosystem instabilities brought about by climate change and stresses, such as land use changes, species dislocation, and increasing global trade and travel, could influence the genetics of pathogenic microbes through mutation and horizontal gene transfer, giving rise to new interactions among hosts and disease agents. Such changes may foster the emergence of new infectious diseases and the need for even stronger food safety measures. Genetically modified food crops and seeds may play a prominent role in food safety by containing genetically manufactured disease-resistant proteins that also repel insects and animal pathogens.

Ethics, culture, and behaviors

The public debate about the ethics and merits of employing genetic modification and other modern biotechnologies in animal and plant breeding is expected to continue, even in the face of increasing evidence of the promise and achievements of biotechnology. Concerns over modern biotechnologies transcend regulators' traditional risk assessment strategies and call for the explicit inclusion of ethical considerations when formulating public policies.

Public pressure to manage odor and waste from animal production is mounting in industrialized economies. Animal welfare concerns are likely to grow, and the European Union and other governments may toughen animal welfare standards.

Concerns over food and meat safety are likely to increase monitoring and testing of animal and food products as well as demand for food scientists, nutritionists, and food research professionals.

Political structures and governance

Stable domestic and regional political structures are likely to negotiate conflict peacefully, reduce political risk associated with investments, and support economic development. Political strife and instability in a country, and conflict between countries affect economic development, security, information sharing, collaboration, and trade.

Governance quality, transparency, and predictability foster investments in the economy and economic development. Political instability and discontinuity in governance may affect policy direction and resource allocation priorities. Countries importing food, fuel, commodities, or industrial goods are particularly vulnerable to external political flux. Increasingly unstable conditions and ongoing regional conflicts may drive some countries to focus on becoming more self-sufficient and independent to improve their national security. This may lead to nationalistic and insular policies.

Scenarios

1. Death by association — Regional pandemic

This scenario involves a regional pandemic that originates from migratory birds and transfers to poultry and other animals. The virus affects humans as well and spreads rapidly. The pandemic hits South East Asia and disrupts animal protein supply chains in the entire region. The pandemic starts as three conditions are met: a new influenza virus subtype emerges; it infects humans, causing serious illness; and it spreads easily and consistently among humans.

The animal health and production and agriculture sectors, research centers, and public health infrastructure are stretched to their limits in identifying outbreaks and containing the pandemic. Groups collaborate to monitor the global food supply and animal production; to decipher the pandemic source, organism, and transmission mechanism; and to develop a vaccine. Researchers in the food industry scramble to develop rapid screening and procedures and low-cost testing kits, as well as to manufacture vaccines to treat/control the pandemic.

The region's entire poultry industry comes to a halt and undergoes rapid purging. Agricultural production slumps as the pandemic hits the farm and animal production sectors. Trade and travel to and from the region stops. High numbers of fatalities occur and the region suffers significant demographic, social, and economic stress.

The equilibrium in the global food supply chain is severely disturbed. Areas and markets surrounding the expanding pandemic footprint purge their poultry industry. Globally, the poultry, animal production, agriculture, and processed food markets experience significant supply and price shocks. Trade policies tighten for food and animal products from the region and cause food importers globally to test and screen food products. Health and safety standards tighten globally as well. Regional economic production slows due to disrupted supply chains, manufacturing and distribution interruptions, and slow or lost sales. These problems spread to the global economy.

Questions arise regarding possible linkages between climate change and the pandemic. Concerns over food and meat safety increase along with demand for monitoring and testing products and for food safety professionals. This scenario highlights the importance of international collaboration, research and development expertise in tracing and containing the pandemic, deciphering the source and transmission mechanism, product development capacity, and manufacturing and supply chain infrastructure to mass produce and deliver vaccines.

2. Cows don't come home — Food defense and safety

This scenario is triggered when a major animal feed processing facility in the United States is intentionally contaminated with the causative agent of bovine spongiform encephalopathy (BSE). The release is initially considered a natural or unintentional event and attempts are made to trace the source of infection. By the time authorities realized that it is a deliberate act, millions of cattle are infected. Since there are no vaccines for BSE, millions of cattle have to be slaughtered.

The national and international effects of this deliberate contamination are significant for humans, food supply, consumer confidence, and national economies. The food production and processing industries face economic and trade disruption because of tightened trade policies and health and safety standards for U.S. animal products, feedstocks, and food crops. U.S. regions that depend heavily on animal production experience economic damage and social disruption. Economic output and growth drop significantly. The equilibrium in the global food supply chain is disrupted. Societies become more aware of the value of food and natural resources and of their vulnerability to food supply shocks.

3. The World of omics, ology, et al. — Rapid technological innovation dominates

This scenario is shaped by rapid technological breakthroughs and innovations in biosciences, along with significant product development. New products that emerge in the food industry in this scenario include nutraceuticals, vaccines, transgenic technologies to manipulate food and animal production, mass delivery of vaccines, xenoproducts and xenotransplants, genomics-based cures, biotechnology applications in food safety using virology, bacteriology and toxicology studies, and nanotechnology applications.

Economic growth and rising food consumption, along with population growth in emerging economies, spur demand for food and animal products. This creates a need for technological innovations. This need is also complemented by demographic changes. The graying of the population in industrialized economies reduces the number of professionals involved in farming and animal production. Urbanization and industrialization in emerging economies reduces the number of people in farming and animal production. These demographic trends fuel demand for improving productivity, improving water and soil supply quality through technological innovations, and product development based on tailoring existing technologies to new applications or regions. The application of industrial practices in food and animal production systems in emerging economies also reinforces demand for technological innovations to create new products suited to local needs.

Average economic growth rates in emerging economies; high food, commodity, and energy prices; and the demographic trends discussed above increase the value of food crops and livestock. These, in conjunction with an emphasis on increasing the productivity of food and animal production systems, drive demand for technological innovation to meet demand for food and animal products.

In this scenario, trade policies continue to be protectionist, but well negotiated between countries and regions. Health and safety regulations and standards are based on a negotiated range of criteria. Environmental regulations are strict, but enlightened. Defined and negotiated ranges of environmental, health, and safety standards and regulations make investments in new technological innovations and product development applicable to larger markets and more attractive to pursue.

Increased globalization of demand and technological innovation either lead to negotiated settlement of ethical concerns regarding biotechnology, or to relegation of these issues to localized undercurrents.

4. "That's hot!" — Climate change concerns dominate

This scenario is driven by increased evidence of, and elevated concerns about, climate change. Scientific evidence linking climate change to potential changing rainfall levels and patterns, changing weather patterns, rising sea levels, and the emergence of new diseases affecting "traditional" local crop production levels and cycles dominates this scenario.

In this scenario, evidence of climate change forces market drivers to shift gears. Social values and pressures increase the emphasis on environmentally sustainable food and animal production. Consumers and citizens place greater value on products, practices, and entities that incorporate climate change considerations. Product labeling and certification of environmentally sustainable practices and processes gain momentum. Water supply availability, soil quality, and environmentally friendly waste disposal are given primary consideration as part of food and animal production. Carbon credits and greenhouse gas emission policies are applied.

Compliance with environmental regulations and standards increases, but mainly to reduce environmental impact and improve sustainability of animal production. Trade regimes become increasingly protectionist with increased emphasis on national food security and self-sufficiency. This trend is particularly strong as production levels and patterns are altered by climate change and cause geographical relocation and distribution of animal and food production.

Energy and commodity prices shoot up because of the imposition of greenhouse gas emissions limits, carbon taxes, and other government policies intended to manage climate change. Compliance results in increased fertilizer costs and, with them, animal feed prices. Greater emphasis on using renewable biomass to replace fossil fuels or to increase organic carbon sinks on land also puts upward pressure on animal feed prices.

Biotechnology applications that reduce waste from food and animal production by altering animal metabolic processes are pursued to improve the environmental impact of animal waste management and disposal. These environmental benefits may also promote greater acceptance of biotechnology in animal and food production.

Climate change alters the geographic distribution of water and soil nutrients. In the short term, this lowers production levels and economic activity until the market reallocates capital and labor to adjust to changing natural resource distribution.

Changes in regional climate patterns caused by long-term global warming affect the potential range of many infectious diseases. The climates of some regions become more suitable to transmit disease agents. Human behavioral adaptations and public and food interventions mitigate many adverse impacts. Another important risk of climate change is its impact on the evolution and emergence of infectious disease agents. Ecosystem instabilities brought about by climate change and stresses, such as land-use changes, species dislocation, and increasing global trade and travel, influence the genetics of pathogenic microbes through mutation and horizontal gene transfer, and give rise to new interactions among hosts and disease agents. Such changes foster the emergence of new infectious diseases and the need for new food products.

Changes in production practices, redistribution of natural resources, and disease emergence and proliferation have demographic impacts. Farming communities experience migration of its population. The population involved in food and animal production requires education to reconfigure food and animal production practices. Understanding, responding to, and anticipating changes in animal and food production require retraining of animal and food production professionals, food scientists, and nutrition researchers. It also requires investments in research and development to understand, respond to, and anticipate changes in animal and food production systems and the animal health system.

Climate change and its interaction with the above drivers create demand for new food products that improve the measurement and mitigation of the environmental impact of animal and food production. Investments in basic and applied research are pursued to respond to climate change. Technologies and surveillance methodologies that rapidly detect emerging diseases are required. Research to alter animal and plant genetics to respond to changing climates, natural resource redistributions, and disease resistance are required. Food products based on genomics, proteomics-based biomarkers for effective diagnostic techniques and disease treatments, and nutrigenomics applications to improve human nutrition are developed to respond to food and animal production health and safety issues arising from climate change.

5. Maslow vs. Malthus — Meeting growing basic needs of a growing population

This scenario is driven most strongly by meeting expanding basic needs. It is a marriage of the Malthusian view that population growth has generally preceded expansion of the population's resources, particularly food, with Maslow's view of the hierarchy of needs, where meeting basic physiological needs such as food and water is the first concern.

In this scenario, sustained, historically average global economic growth rates have expanded the demand for resources, including food, water, and nutrient-rich soil. This is a world of tight food, energy, and commodity markets.

As economic growth lifts more people out of poverty, demand for food and animal products for a richer and more varied diet increases. Increased attention to malnutrition and global hunger also drives demand for food and animal products. Demographic shifts such as rural-to-urban migration in emerging economies because of urbanization and industrialization reduces the population associated with animal and food production. In industrialized economies, the graying of the population reduces the population in animal and food production. These demographic trends create a need to improve the productivity of food and animal production resources through technological improvements.

Tightening food and commodity markets lead to protectionist and nationalistic policies to achieve food security and food sufficiency by some countries. Food and animal production subsidies increase in countries and regions, fiscal space permitting. Increased retention of local animal and food production in a world of increasing trade creates stronger technical barriers to trade. This leads to strategies targeted at imports, such as country-of-origin labeling, certification of responsible production systems, and certification and standardization of production and distribution processes. Countries that are highly dependent on imports of animal and food products liberalize imports further to attract a larger share of world trade.

Increasing demand for food and animal products translates into higher demand for animal protein, modification of existing products tailored to new geographical markets, and product development based on an average rate of technological change.

Social concerns for animal welfare are local and limited, and dominated by concerns about feeding the population. In emerging economies, increasing demand for food and water affordability, safety, and availability trump emphasis on animal welfare. In industrialized economies, greater dependence on fewer farming and animal producers subdue animal welfare concerns. Concerns about water availability and soil quality take precedence over needs for further urbanization and large-lot development. Debates about the use of biotechnology for food and animal production are local or regional, but the dominant issue at the global level is to fill stomachs of a larger population.

Concerns about climate change are driven by utilitarian motives. Evidence of climate change affects animal and food production. This leads to investments in research and development, technologies, and food products that make animal and food production more environmentally sustainable.

6. Boom — Rapid economic growth

This scenario is dominated by an economic boom. Rapid economic growth expands demand for food and animal products. Global food trade increases because of rising demand for animal protein, high nutrient count crops, and richer, more diversified diets. Competition for biomass for food, animal feed, and biofuel applications grows. Energy, commodity, and food prices elevate animal livestock values and food prices. Health and safety standards and regulations are enlightened, but appropriate for monitoring the growing food supply chain.

Demographic forces strongly influence this scenario. The graying of the population in industrialized economies reduces the number of professionals in farming and animal production. Demand is significant for professionals and products for food testing and surveillance of the global supply chain. Urbanization and industrialization in emerging economies reduce the number of people in farming and animal production. The application of industrial practices in animal and food production systems in emerging economies also reinforces demand for technological innovations to create new products suited to local needs. These trends create a talent shortage of professionals in food and animal production.

Product development is significant, but technological innovation occurs at an average rate with limited technological breakthroughs. Rapid technological breakthroughs are constrained by unresolved ethical debates. Innovation is predominantly from product development based on technologies where ethical issues have been resolved. The debate about the use of biotechnology for food and animal production is unresolved and remains an obstacle to rapid technological innovation. Social concerns for animal welfare are contested by increased dependence on fewer farming and animal production facilities and emphasis on meeting demand for animal products.

Limited concerns for climate change lead to investments to make animal and food production more environmentally sustainable to attain utilitarian objectives of meeting high economic growth rates.

Demographic pressures affecting demand and supply of animal products, rapid economic growth, and high energy, commodity, and food prices contribute to product development that is constrained by ethical concerns about biotechnology in industrialized economies, which limits technological breakthroughs. New nutraceuticals, vaccines, and food safety products utilizing virology, bacteriology, and toxicology are some of the products that are developed in this scenario.

7. Slippage — Below-average global economic growth

This scenario is dominated by below-average global economic growth and low energy, commodity, and food prices. Low economic growth rates decelerate the demand for food and animal products.

The graying of the population in industrialized economies is a key factor in pushing for productivity gains in food and animal production through animal health products. In emerging economies, lower economic growth rates decelerate food and animal product demand. However, momentum exists to adapt and develop food and animal production technology for emerging markets reflecting a Malthusian view of resource pressures to meet growing population needs. Demand for developing food production and processing infrastructure in emerging economies is significant.

Trade in food and animal products is static or experiences slow growth; trade policies are protectionist. Elevated concerns for health and safety issues related to genetically modified food crops and animal welfare are in the forefront of some societies. Environmental, health and safety, and product-labeling standards are significant and varied. The economic and trade systems are fragmented with multiple sets of policies, standards, and regulations. There is higher demand for food scientists, food safety professionals, nutrition researchers, and laboratory technicians. Demand also increases for food safety products, such as testing and detection kits and supply chain monitoring and testing.

These economic, demographic, and social forces fuel new product development tempered by slower economic growth and fragmentation.

8. One world — System of connected sub-systems

This scenario describes the world as one system. There is one global ecosystem that consists of climate systems and weather patterns. Worldwide, trade, natural resources, and talent are each composed of interdependent sub-systems. Disease outbreak in one region has the potential to spread to other regions with varying capacities to resist the outbreak and varying impacts. Resource use and stresses leading to commodity price increases in one large economy affect prices globally. Disease emergence in animal species affects human condition. The world is interconnected and complex networks of sub-systems that have both unique and common features.

In this scenario, the ecosystem is treated as one system that must be protected by all citizens of the planet. Climate change is viewed as a global issue with all countries responsible for addressing climate change. Negotiated ranges of policies, standards, and regulations govern the production, trade, health and safety, and environmental sustainability of food and animal production and food products. Negotiated definitions address animal welfare standards, primary water supply availability, soil quality protection, and the ethics of biotechnology and genetically modified products. The global food supply chain is monitored through collaborations of surveillance networks with the participation of government, academia, and industry.

There are higher levels of "fair trade" flows. Subsidies have been gradually reduced and resource allocation is viewed from a global perspective. The global economy has grown at a historically average rate. Energy, commodity, and food prices reflect costs of negative externalities, such as greenhouse gas emissions, carbon, and other costs associated with maintaining environmentally sustainable economic activities.

Urbanization and industrialization in emerging economies coupled with the graying of the population in industrialized economies continues the talent shortage in food and animal production, food science, food nutrition and health research, and veterinary professionals. Technological innovation takes place at an average rate and new products emerge because of product development based on existing technologies. Collaborations and international standardization lead to development of food products to cater to bigger markets. There are limited large-scale investments and technological breakthroughs in the food industry.

9. Consumer's world — Consumer preferences dominate

Consumer preferences dominate this scenario. Consumers are concerned about health and wellness, food as a source of nutrition, local produce and products, and environmental sustainability. The challenge facing food and beverage companies is to have balance, including locally produced and sustainable products, to address consumer preferences while simplifying their production and delivery to better manage costs. Food products cannot be fully replaced by local or organic products. The trade of food products requires greater evidence of health, nutritional, and product-value attributes. Consumer preferences for environmentally sustainable practices spur carbon footprint labeling or certification of sustainable farming and production practices. The "food miles" from "farm to fork" are emphasized as energy costs continue to rise.

Sustained economic growth allows high-income consumers to demand products that are high in nutrient content, organic, antibiotic-free, and natural, such as those that come directly from farmers' markets and food coops. Consumers demand drops for less healthy food products, high in trans fat and sodium, which may be more convenient to consume, but impose a greater health cost.

Policies, standards, and regulations require a local focus along with a global focus. This may cause markets to be fragmented according to local policies, standards, and regulations if local policymakers do not adopt regional or national standards.

A shift toward sustainability leads food producers in industrialized economies to invest in environmentally friendly and energy-efficient machinery to meet local food and animal production needs.

Changes in market dynamics favoring consumption of local foods have an immediate and sustained impact. The population involved in local food and animal production requires education to reconfigure food and animal production practices to focus on local requirements and sustainability. Local food production drives demand for local food scientists and technicians, food safety professionals, and nutrition researchers.

Younger farmers adopt new technologies, such as biotechnology to provide disease resistance to plant and animal pathogens, nutrigenomics for personalized prevention and treatment of nutrition-related diseases, bio-water savings through plant water-use efficiency, information systems and biosensors for food monitoring, and molecular marker technologies to select and recombine superior plant breeding traits.

Table 7 on the next page summarizes the scenarios defined by different states of all the drivers.

Table 7: Summary of scenarios

	Science and technology	Demography	Economy	Policies, standards, and regulations	Energy, commodity, and input prices	Climate and the environment	Ethics, culture, and behaviors	Political structures and governance
Death by association — Regional pandemic	Immediate demand for testing, tracing, and containing pandemic, and for developing vaccines and mass producing them.	Population involved in animal production and farming communities severely affected. Significant decline in populations in the region.	Animal and food production severely affected in the region. Poultry sector culled. Supply and price shock to the regional animal protein market. Global food supply chain interrupted.	Trade regulations, safety standards, environmental regulations tighten.	No effect and average prices remain pre- and post-pandemic.	Concerns are elevated about the potential connection of the outbreak to climate change.	Societies become aware of value of food and natural resources.	Policies are quickly realigned. Governance disruptions caused by demographic and economic shock.
Cows don't come home — Food defense and safety	Immediate demand for testing, tracing, and containing disease, and for developing vaccines and mass producing them.	Population involved in animal production and farming communities severely affected. Significant decline in populations in the region.	Animal and food production severely affected in the region. Dairy sector culled. Supply and price shock to the regional animal protein and dairy market. Global food supply chain interrupted.	Trade regulations, safety standards, environmental regulations tighten.	No effect and average prices remain pre- and post-pandemic.	Limited concerns of climate change's impact on food and animal production.	Societies become aware of value of food and natural resources.	Policies are quickly realigned.
The world of omics, ology, et al. — Rapid technological innovation dominates	Rapid technological innovation. Breakthroughs in basic and applied research leading to cutting edge products.	High demand and talent shortage of food safety, food scientists, nutrition researchers, and animal health professionals.	Average global economic growth.	Net effect is neutral. Protectionist trade policies. Enlightened environmental and food safety regulations.	High food, commodity, and energy prices. Competition for biomass.	Limited concerns of climate change's impact on food and animal production.	Negotiated settlement of ethical concerns of biotechnology or relegation of these issues to localized undercurrents.	Predictable and long-term policy direction supporting technological innovation and investments.
"That's hot!" — Climate change concerns dominate	Demand and rate of product development and technological innovation are high	Climate change shifting agriculture and animal production practices and locations. High demand for retraining farmers, animal production workforce, and R&D teams. Talent shortage of food scientists, food safety professionals, nutrition researchers, and animal health professionals.	Low-to-average global economic growth. Food and animal production affected by climate change.	Protectionist trade regimes due to increased emphasis on national food security and self-sufficiency. Increased zoonotic disease emergence forces increased health and safety standards. Environmental regulations increased for food and animal products, including health products.	High food, commodity, and energy prices that reflect costs of negative externalities, such as greenhouse gas emissions, carbon, and other costs associated with environmentally sustainable economic activity.	Elevated concerns and evidence of climate change affecting food and animal production.	Societies value, widely endorse, and practice sustainable consumption and social values.	Policy realignment due to demographic and economic changes. Governance structures realigned.
Maslow vs. Malthus — Meeting growing basic needs of a growing population	Average rate of product and technological development.	Increasing demand for products from a smaller pool of farmers and ranchers. Talent shortage of food scientists, food safety professionals, nutrition researchers, and animal health professionals.	Historically average global economic growth.	Nationalistic policies for increasing food security. Higher retention of domestic output. Liberalized import regimes by import dependent societies	Tight food, commodity, and energy markets.	Utilitarian climate change concerns to ensure increasing food production	Mixed emphasis on food and animal welfare and ethics of biotechnology, which varies between developed and emerging economies.	Nationalist policies create regional tensions.
Boom — Rapid economic growth	Average technological innovation.	Increasing demand for products from a smaller pool of farmers and ranchers. Talent shortage of food scientists, food safety professionals, nutrition researchers, and animal health professionals.	Rapid global economic growth.	Enlightened but significant health and safety standards and regulations to monitor growing food supply chain.	High food, commodity, and energy prices. Competition for biomass.	Limited and utilitarian concerns for climate change.	Ethical issues on deployment of technologies remain. Resistance to biotechnology applications.	Technological innovation affected by policies and social concerns about ethics of biotechnology.
Slippage — Below-average economic growth	Below-average rate of technological change	Graying of farmers and ranchers, food scientists, food safety professionals, and nutrition researchers in developed countries	Below-average global economic growth.	Protectionist trade policies. Strict health and safety standards for traded food and animal products, and hence food and animal health products.	Low food, commodity, and energy prices.	Limited concerns of climate change's impact on food and animal production.	Elevated concerns for food and animal welfare. Debate on the ethics and merit of biotechnology roaring.	Policy posture protectionist and nationalistic. Predictable governance.
One world — System of connected sub-systems	Average rate of technological innovation. Above-average rate of product development.	Talent shortage globally. Increasing international collaborations between academia, industry, and research institutions.	Average global economic growth.	Unified health and safety and environmental sustainability standards. Collaborative food supply monitoring and surveillance systems/ networks.	Prices reflect costs of negative externalities such as greenhouse gas emissions, carbon, and other costs associated with environmentally sustainable economic activity.	Climate change and environmental protection as a global collaborative concern.	Negotiated definitions of food and animal welfare standards, ethics of biotechnology, and genetically modified products.	Enlightened and globally negotiated, coordinated policies. Predictable, transparent, governance.
Consumer's world — Consumer preferences dominate	Above-average technological innovation and application of technologies. New demand for locally produced, healthy, safe food spurs regional innovations.	Graying population is relieved by younger generation of farmers and ranchers to fulfill demand for local food and animal products. New local roles for food scientists, food safety professionals, and nutrition researchers are filled.	Increasing and sustainable economic growth. Less global trade for food and animal products due to desire for local products.	Net effect is neutral. Regulations are static and less focused on food export given the desire to grow and produce food locally. Food safety continues to be a focus and regional knowledge improves safety of food.	Energy prices for non-renewable sources continue to increase, but are offset by alternative energy sources. Grain and food commodity prices increase, but local production provides ample alternatives for producing regional identity food preferences.	Climate change is less than anticipated due to sustainability practices and lowering of greenhouse gas emissions through more energy efficient and environmentally friendly technologies and production practices.	Concerns for buying from local producers, organic, antibiotic free, and high nutritional value. Decrease in desire for mass-produced, low-nutrition, and high calorie foods. Carbon footprint and "food miles" become important to consumers.	Policies affected by consumer preferences. Predictable governance.

Product and technology portfolios and enabling knowledge clusters

The next step is to identify the relevant technology and product portfolios across scenarios. They are summarized in Table 8. In the absence of constraints specific to decision makers, we identify a range or portfolio of technologies relevant across scenarios. Decision makers can choose the technologies suitable for their institutions' mission and resources. The objective of this table is to identify how different products and technologies are relevant across different scenarios. We have developed a range of scenarios based on our understanding of currently available information to identify products, technologies, and knowledge clusters that are expected to shape the industry in the future. This is not a predictive exercise aimed at arriving at one exact answer. This is an exercise aimed to explore a range of opportunities in the future. Reasonable people could argue and conclude differently with our point of view based on knowledge available to them or evolving market dynamics.

Table 8: Product and technology portfolios

		Scenarios								
Technologies	**Products**	**Death by association**	**Cows don't come home**	**The world of omics, ology et al.**	**"That's hot!"**	**Maslow vs. Malthus**	**Boom**	**Slippage**	**One world**	**Consumer's world**
Molecular biology / microbiology										
Protein manipulation at the molecular level	Molecular docking proteins with improved hit identification and maximized lead optimization to enhance nutrient delivery of drug/bio treatments through food			✓		✓	✓		✓	
Protein sensing and monitoring	Microbiology sensing products to detect spoilage in agriculture and animal products (priority is for muscle foods)			✓		✓			✓	
Genetic engineering										
Genome sequencing and mapping	Integrated genetic map with over 17,000 markers from other linkage and hybrid maps from around the world			✓	✓	✓	✓			
Genome sequencing and mapping	Generated and annotated cDNA sequences for improving animal feed efficiency and environmental sustainability			✓	✓	✓				
Genome sequencing and mapping	Bovine genome tools to develop gene selection methods			✓	✓	✓				
Proteomic combinations for better health	Transgenic animals to supply pharmaceutical proteins and transplantable organs for humans			✓		✓				
Proteomic combinations for better health	Metabolic pathway combinations to produce rare and expensive natural products, making them more affordable to produce			✓	✓	✓		✓		
Proteomic combinations for better health	Functional enhancement by increasing genetic properties of foods (e.g., high-antioxidant and low-allergenicity content)			✓		✓				
Proteomic combinations for better health	Efficient combination of proteins to produce foods more affordably				✓	✓		✓		
High-throughput biology	Clonal seed production of crops so that any hybrid varieties breed true and shorten time to market				✓	✓	✓		✓	✓
Environmental sustainability										
Bioengineering for improved functionality	Food crops with increased efficiency in transpiration and photosynthesis (bio-water)			✓	✓	✓	✓		✓	✓
Bioengineering for improved functionality	Food crops with RSFR properties			✓	✓	✓	✓			✓
Bioengineering for improved functionality	Inorganic fertilizers			✓	✓					
New planting and production techniques with sustainable resources and materials	Use of halophyte plants to provide seawater irrigation and use of saline aquifers; genomics can play a role in enhancing halophyte water desalination efficiency			✓	✓				✓	✓
New planting and production techniques with sustainable resources and materials	Local crop generation to meet local demand offers the greatest use of next generation technologies to sustain the environment			✓	✓				✓	✓
Nutrigenomics										
Proteomic combinations for better health	Customization of foods based on nutrition/dietary needs				✓		✓			✓
Proteomic combinations for better health	Customization of foods to help treat chronic, sub-acute, and acute diseases/infections (e.g. cancers, type-2 diabetes, Chrons disease, high blood pressure, flu, and rashes)			✓	✓		✓			✓
Food supply chain information systems										
Bioinformatics systems and solutions	Bioinformatics for DNA matrix arrays containing annotated sequences and linkage/hybrid maps and other genetic makeup data	✓	✓	✓	✓	✓				
Supply chain technology infrastructure and monitoring tools	ICTs - Information Communication Technologies that link the field to the check out lane for food and animal products			✓		✓	✓			

Table 8: Product and technology portfolios (continued)

Technologies	Products	Scenarios: Death by association	Cows don't come home	The world of omics, ology et al.	"That's hot!"	Maslow vs. Malthus	Boom	Slippage	One world	Consumer's world
Supply chain technology infrastructure and monitoring tools	Virtual Enterprise Networks - connections between industry, academic, and government research resources			✓	✓		✓		✓	
Supply chain technology infrastructure and monitoring tools	Collaborative design technologies for use with food and animal product manufacturers, food packaging manufacturers, and distributors			✓	✓	✓		✓	✓	
Supply chain technology infrastructure and monitoring tools	Supply chain integration with regulatory agencies to accelerate containment of recalled food and animal products	✓	✓		✓		✓		✓	
Food safety / biological containment										
Food safety systems, technology, and monitoring tools	Biosensors integration within the food supply chain monitoring for changes to safety of food and animal resources, products, and sharing of food safety leading practices	✓	✓	✓	✓		✓		✓	
Food safety systems, technology, and monitoring tools	Biological containment systems for isolating contaminated food crops and animals and to prevent crossbreeding/pollination of genetically modified food crops and animals	✓	✓	✓	✓	✓	✓		✓	✓
Food safety systems, technology, and monitoring tools	Rapid and efficient transcriptomics, proteomics, and biosensor-based technologies are in development for detecting a wide variety of contaminants	✓	✓	✓						
Nanotechnology										
Packaging utilizing nanotech and materials science	Multi-functional packaging (keeps food cold without freezing or packaging adhering to product)			✓	✓	✓	✓		✓	
Packaging utilizing nanotech and materials science	Anti-microbial packaging designed to seek and destroy food contaminants and microorganisms			✓	✓	✓	✓		✓	
Food protection additives using nanotech and materials science	Nanosensor materials that detect toxins, chemicals, and pathogens and alert consumer to their contents prior to exposure			✓	✓	✓				
Food protection additives using nanotech and materials science	Nanocoatings designed to serve as repellents to dirt, fungi, and other unwanted product contaminants			✓						
Packaging utilizing nanotech and materials science	Nanotubes, nanowheels, nanofibers can be used to ensure efficient breakdown of packaging material for recycling/recombination			✓	✓					
Green chemistry										
Packaging utilizing nanotech and materials science	Reduction or elimination of hazardous substances using advanced polymeric materials in food packaging; biopolymers, nanotechnology and nanocomposites, and active and intelligent packaging properties are all potential green chemistry packaging materials			✓	✓					
Packaging utilizing nanotech and materials science	Biological-based materials with nanotechnology would provide products for flexible and rigid packaging sectors				✓		✓			
Non-thermal food processing										
Sterilization from radiation, electricity, magnetic, or carbon dioxide-based food processing technologies	Ionizing radiation from pulsed x-rays, pulsed light and electric fields, high-voltage arc discharge, magnetic fields, dense phase carbon dioxide (CO_2)	✓	✓	✓	✓	✓	✓			
Sterilization from nanotech and materials science food processing technologies	Hurdle technologies that include new packaging materials			✓						
Resource purification										
Purification technologies improving availability of sustainable resources with minimal by-products	Disinfection of water to remove low-concentration contaminants and provide ability to re-use waste water with minimal toxic by-products; use of photons and engineered nanostructures, and microorganism-based technologies				✓				✓	✓
Drug / biological treatment delivery										
Food products capable of drug/biological treatment delivery	Foods designed for drug/biologic delivery	✓	✓							
Food products capable of drug/biological treatment delivery	Snacks to be taken over several days to release the correct drug dosage	✓	✓							
Basic ingredients and additives used to deliver drug and biological treatments	Basic ingredients and food additives designed to be cooked with/combined with other foods to release the correct drug dosage over several days	✓	✓						✓	
High nutrition and environmentally sustainable food products										
Proteomic combinations for better health	Organic food and animal products from local sources that contain nutritional elements based on specific dietary needs						✓			✓
Proteomic combinations for better health	Genetically modified food and animal products that contain high-nutrient levels from high-efficiency crop yields and livestock			✓	✓	✓		✓	✓	

It is also possible to determine knowledge clusters needed to develop the technologies and products. Table 9 presents the definitions of knowledge clusters of interest. Table 10 shows knowledge clusters that would be necessary to develop technologies or products. Based on their constraints and capabilities, decision makers can choose which knowledge cluster to build or strengthen. Table 10 presents the rationale for the relevance of knowledge clusters for the products and technologies. Table 11 presents a summary of the knowledge clusters necessary for developing products and technologies.

Table 9: Definitions of knowledge clusters

Knowledge cluster	Definition
Catalysis	Catalysis is the process in which the rate of a chemical or biological reaction is increased by means of a chemical or biological substance known as a catalyst or an enzyme, respectively.
Synthesis	Synthesis is a purposeful execution of chemical or biological reactions in order to get a product or several products.
Bioengineering	Bioengineering is the application of a systematic, quantitative, and integrative way of thinking about and approaching the solutions to problems important in biology, medical research, clinical proactive, and population studies. It integrates physical, chemical, or mathematical sciences and engineering principles for the study of biology, medicine, behavior, or health.
Clinical capabilities	Clinical capability is the ability to deliver health care in a systematic setting and the ability to conduct research on new diagnostics and therapies in a health care or clinical setting that may involve support from contract research organizations.
Systems biology	Systems biology is the study of biological systems to elucidate their components and their dynamical interplay in order to understand the functioning of the system as a whole. Systems biology is the study of an organism, viewed as an integrated and interacting network of genes, proteins and biochemical reactions, which give rise to life. Instead of analyzing individual components or aspects of the organism, such as sugar metabolism or a cell nucleus, systems biologists focus on all the components and the interactions among them, all as part of one system.
Genomics and proteomics	Genomics is the study of an organism's entire genome. This includes determining the DNA sequence and genetic mapping. Proteomics is the study of proteins, particularly their structures and functions.
Nanotechnology	Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale.
Materials science	Materials science is an interdisciplinary field involving the properties of matter and its applications to various areas of science and engineering. This science investigates the relationship between the structure of materials and their properties. It includes elements of applied physics and chemistry, as well as chemical, mechanical, civil, and electrical engineering.
Imaging / navigation	Imaging science is concerned with the generation, collection, duplication, analysis, modification, and visualization of images. As an evolving field it includes research from physics, mathematics, electrical engineering, computer vision, computer science, and perceptual psychology, among others.
Computer science	Computer science is the study of the theoretical foundations of information and computation and their implementation and application in computer systems. Computer science is the study of the storage, transformation, and transfer of information. The field encompasses both the theoretical study of algorithms (including their design, efficiency, and application) and the practical problems involved in implementing them in terms of computer software and hardware.
Data management and analysis	Data management is the development and execution of architectures, policies, practices, and procedures that properly manage the full data lifecycle needs of an enterprise.

Table 10: Table of technologies and knowledge clusters

Technologies	Products	Basis for knowledge cluster
Molecular biology / microbiology		
Protein manipulation at the molecular level	Molecular docking proteins with improved hit identification and maximized lead optimization to enhance nutrient delivery of drug/bio treatments through food	Catalysis, synthesis, bioengineering, genomics, and proteomics for developing new drugs. Nanotechnology expertise for both delivery and drug product. Require large data processing and management.
Protein sensing and monitoring	Microbiology sensing products to detect spoilage in agriculture and animal products (priority is for muscle foods)	Nanobiotechnology-based testing devices. Genomics expertise for developing tests. Require large data processing and management.
Genetic engineering		
Genome sequencing and mapping	Integrated genetic map with over 17,000 markers from other linkage and hybrid maps from around the world	Systems biology for understanding animal and plant systems. Genomics and proteomics for gene mapping and bioinformatics for data analysis and gene integration.
Genome sequencing and mapping	Generated and annotated cDNA sequences for improving animal feed efficiency and environmental sustainability	Systems biology for understanding animal and plant systems. Genomics and proteomics for gene mapping and bioinformatics for data analysis and gene integration.
Genome sequencing and mapping	Bovine genome tools to develop gene selection methods	Genomics, proteomics, and bioengineering for gene manipulation to improve animal food product. Systems biology for understanding processes in animal systems. Require large data processing and management.
Proteomic combinations for better health	Transgenic animals to supply pharmaceutical proteins and transplantable organs for humans	Systems biology to understand the animal and human systems for transplants. Bioengineering for immunogenecity and compatibility of pharmaceutical proteins and transplantable organs. Bioengineering, genomics, and proteomics for developing new xenobiotics. Bioinformatics to data analysis and manipulation. Catalysis and synthesis of complimentary products for transplantation.
Proteomic combinations for better health	Metabolic pathway combinations to produce rare and expensive natural products, making them more affordable to produce	Catalysis and synthesis of natural products. Systems biology for understanding animal and plant systems.
Proteomic combinations for better health	Functional enhancement by increasing genetic properties of foods (e.g., high-antioxidant and low-allergenicity content)	Catalysis and synthesis of functional food additives. Bioengineering, genomics, and proteomics for gene manipulation to improve food products. Nanotechnology for nanofood design.
Proteomic combinations for better health	Efficient combination of proteins to produce foods more affordably	Catalysis, synthesis, bioengineering, genomics, and proteomics for protein manipulation to improve food products. Nanotechnology for nanofood design.
High-throughput biology	Clonal seed production of crops so that any hybrid varieties breed true and shorten time to market	Systems biology for understanding processes in plant systems. Genomics, proteomics, and bioengineering for gene manipulation. Bioinformatics for genomic data analysis and manipulation.
Environmental sustainability		
Bioengineering for improved functionality	Food crops with increased efficiency in transpiration and photosynthesis (bio-water)	Systems biology for understanding processes in plant systems. Genomics, proteomics, and high throughput biology, bioengineering for gene manipulation. Bioinformatics for data analysis and manipulation. Catalysis and synthesis expertise for understanding plant processes.
Bioengineering for improved functionality	Food crops with RSFR properties	Systems biology for understanding processes in plant systems. Genomics, proteomics, and high throughput biology, bioengineering for gene manipulation. Bioinformatics for data analysis and manipulation.
Bioengineering for improved functionality	Inorganic fertilizers	Catalysis expertise for understanding nutrient absorption and also fertilizer product. Materials sciences and nanotechnology for synthesized nutrients.
New planting and production techniques with sustainable resources and materials	Use of halophyte plants to provide seawater irrigation and use of saline aquifers; genomics can play a role in enhancing halophyte water desalination efficiency	Systems biology for understanding processes in plant systems. Genomics, proteomics, and high throughput biology, bioengineering for gene manipulation. Catalysis and synthesis expertise for understanding plant processes. Materials sciences and nanotechnology for development of saline aquifers.
New planting and production techniques with sustainable resources and materials	Local crop generation to meet local demand offers the greatest use of next generation technologies to sustain the environment	Systems biology for understanding processes in plant systems. Genomics, proteomics, and bioengineering for gene manipulation.
Nutrigenomics		
Proteomic combinations for better health	Customization of foods based on nutrition/dietary needs	Systems biology for understanding processes in animal systems. Genomics, proteomics, and bioengineering for gene manipulation. Catalysis and synthesis of dietary additives. Bioinformatics for data analysis.
Proteomic combinations for better health	Customization of foods to help treat chronic, sub-acute, and acute diseases/infections (e.g. cancers, type-2 diabetes, Crohn's disease, high blood pressure, flu, and rashes)	Systems biology for understanding processes in animal systems. Genomics, proteomics, and bioengineering for gene manipulation. Catalysis and synthesis of dietary additives. Bioinformatics for data analysis.
Food supply chain information systems		
Bioinformatics systems and solutions	Bioinformatics for DNA matrix arrays containing annotated sequences and linkage/hybrid maps and other genetic makeup data	Genomics, proteomics, and bioengineering for handling DNA microarrays. Bioinformatics for data management and analysis.
Supply chain technology infrastructure and monitoring tools	ICTs - Information Communication Technologies that link the field to the check out lane for food and animal products	Bioinformatics for food supply data analysis. Materials science and nanotechnology for devices that monitor and transmit data.
Supply chain technology infrastructure and monitoring tools	Virtual Enterprise Networks - connections between industry, academic, and government research resources	Bioinformatics for food supply data analysis. Materials science and nanotechnology for devices that monitor and transmit data.
Supply chain technology infrastructure and monitoring tools	Collaborative design technologies for use with food and animal product manufacturers, food packaging manufacturers, and distributors	Bioinformatics for food supply data analysis. Materials science and nanotechnology for devices that monitor and transmit data.
Supply chain technology infrastructure and monitoring tools	Supply chain integration with regulatory agencies to accelerate containment of recalled food and animal products	Nanobiotechnology-based testing devices. Bioinformatics for food supply data analysis. Materials science and nanotechnology for devices that monitor and transmit data.
Food safety / biological containment		
Food safety systems, technology, and monitoring tools	Biosensors integration within the food supply chain monitoring for changes to safety of food and animal resources, products, and sharing of food safety leading practices	Nanobiotechnology-based biosensors/testing devices. Genomics expertise for developing tests. Systems biology for understanding the integration of biosensors in animal systems. Bioinformatics for online testing and data processing.
Food safety systems, technology, and monitoring tools	Biological containment systems for isolating contaminated food crops and animals and to prevent crossbreeding/ pollination of genetically modified food crops and animals	Nanobiotechnology-based containment structures. Genomics expertise for developing tests. Bioinformatics for online testing and data processing. Materials science for containment systems.
Food safety systems, technology, and monitoring tools	Rapid and efficient transcriptomics, proteomics, and biosensor-based technologies are in development for detecting a wide variety of contaminants	Nanobiotechnology-based biosensors/testing devices. Genomics expertise for developing tests. Systems biology for understanding the integration of biosensors in animal systems. Bioinformatics for online testing and data processing.

Table 10: Table of technologies and knowledge clusters (continued)

Technologies	Products	Basis for knowledge cluster
Nanotechnology		
Packaging utilizing nanotech and materials science	Multi-functional packaging (keeps food cold without freezing or packaging adhering to product)	Materials science and nanotechnology for developing coatings. Catalysis and synthesis of biopolymers.
Packaging utilizing nanotech and materials science	Anti-microbial packaging designed to seek and destroy food contaminants and microorganisms	Materials science and nanotechnology for developing coatings. Catalysis and synthesis of biopolymers. Bioinformatics for data analysis.
Food protection additives using nanotech and materials science	Nanosensor materials that detect toxins, chemicals, and pathogens and alert consumer to their contents prior to exposure	Catalysis and synthesis of food additives. Nanobiotechnology-based testing devices. Bioinformatics for data analysis. Imaging, materials science, and nanotechnology for devices that monitor and transmit data.
Food protection additives using nanotech and materials science	Nanocoatings designed to serve as repellents to dirt, fungi, and other unwanted product contaminants	Materials science and nanotechnology for developing coatings. Bioinformatics for data processing.
Packaging utilizing nanotech and materials science	Nanotubes, nanowheels, nanofibers can be used to ensure efficient breakdown of packaging material for recycling/ recombination	Materials science and nanotechnology for developing coatings. Bioinformatics for data processing.
Green chemistry		
Packaging utilizing nanotech and materials science	Reduction or elimination of hazardous substances using advanced polymeric materials in food packaging; biopolymers, nanotechnology and nanocomposites, and active and intelligent packaging properties are all potential green chemistry packaging materials	Catalysis and synthesis of biopolymers. Nanobiotechnology-based testing devices. Bioinformatics for data analysis. Imaging, materials science and nanotechnology for devices that monitor and transmit data.
Packaging utilizing nanotech and materials science	Biological-based materials with nanotechnology would provide products for flexible and rigid packaging sectors	Catalysis and synthesis of biopolymers. Nanobiotechnology-based testing devices. Imaging, materials science and nanotechnology for devices that monitor and transmit data.
Non-thermal food processing		
Sterilization from radiation, electricity, magnetic, or carbon dioxide-based food processing technologies	Ionizing radiation from pulsed x-rays, pulsed light and electric fields, high-voltage arc discharge, magnetic fields, dense phase carbon dioxide (CO_2)	High-throughput biology for developing technologies based on physical and biological sciences.
Sterilization from nanotech and materials science food processing technologies	Hurdle technologies that include new packaging materials	Catalysis and synthesis of biopolymers. Nanobiotechnology-based testing devices. Bioinformatics for data analysis. Materials science and nanotechnology for devices that monitor and transmit data.
Resource purification		
Purification technologies improving availability of sustainable resources with minimal by-products	Disinfection of water to remove low-concentration contaminants and provide ability to re-use waste water with minimal toxic by-products; use of photons and engineered nanostructures, and microorganism-based technologies	Catalysis and synthesis of biopolymers. Materials science and nanotechnology for engineered nanostructures, and microorganism-based technologies.
Drug / biological treatment delivery		
Food products capable of drug/biological treatment delivery	Foods designed for drug/biologic delivery	Catalysis and synthesis, bioengineering, genomics, and proteomics for developing new drugs. Nanotechnology expertise for both delivery and drug product.
Food products capable of drug/biological treatment delivery	Snacks to be taken over several days to release the correct drug dosage	Catalysis and synthesis, bioengineering, genomics, and proteomics for developing new drugs. Nanotechnology expertise for both delivery and drug product.
Basic ingredients and additives used to deliver drug and biological treatments	Basic ingredients and food additives designed to be cooked with/combined with other foods to release the correct drug dosage over several days	Catalysis and synthesis, bioengineering, genomics and proteomics for developing new drugs. Nanotechnology expertise for both delivery and drug product.
High nutrition and environmentally sustainable food products		
Proteomic combinations for better health	Organic food and animal products from local sources that contain nutritional elements based on specific dietary needs	Genomics and proteomics for gene manipulation to improve nutrition. Systems biology for understanding processes in animal systems. Bioinformatics for data analysis.
Proteomic combinations for better health	Genetically modified food and animal products that contain high-nutrient levels from high-efficiency crop yields and livestock	Genomics, proteomics, and bioengineering for gene manipulation to improve nutrition. Systems biology for understanding processes in animal systems. Bioinformatics for data analysis.

Table 11: Summary of technologies and knowledge clusters

Technologies	Products	Catalysis	Synthesis	Bioengineering	Clinical capabilities	Systems biology	Genomics and proteomics	Nanotechnology	Materials science	Imaging/ navigation	Computer science	Data management and analysis
Proteomics												
Protein manipulation at the molecular level	Molecular docking proteins with improved hit identification and maximized lead optimization to enhance nutrient delivery of drug/bio treatments through food	✓	✓	✓	✓		✓	✓			✓	✓
Protein sensing and monitoring	Microbiology sensing products to detect spoilage in agriculture and animal products (priority is for muscle foods)						✓	✓			✓	✓
Genetic engineering												
Genome sequencing and mapping	Integrated genetic map with over 17,000 markers from other linkage and hybrid maps from around the world					✓	✓				✓	✓
Genome sequencing and mapping	Generated and annotated cDNA sequences for improving animal feed efficiency and environmental sustainability			✓	✓	✓	✓				✓	✓
Genome sequencing and mapping	Bovine genome tools to develop gene selection methods			✓		✓	✓				✓	✓
Proteomic combinations for better health	Transgenic animals to supply pharmaceutical proteins and transplantable organs for humans	✓	✓	✓	✓	✓	✓				✓	✓
Proteomic combinations for better health	Metabolic pathway combinations to produce rare and expensive natural products, making them more affordable to produce	✓	✓			✓	✓					
Proteomic combinations for better health	Functional enhancement by increasing genetic properties of foods (e.g., high-antioxidant and low-allergenicity content)	✓	✓	✓			✓	✓				
Proteomic combinations for better health	Efficient combination of proteins to produce foods more affordably	✓	✓	✓			✓	✓				
High-throughput biology	Clonal seed production of crops so that any hybrid variety breeds true; shortens time to market			✓		✓	✓				✓	✓
Environmental sustainability												
Bioengineering for improved functionality	Food crops with increased efficiency in transpiration and photosynthesis (bio-water)	✓	✓	✓		✓	✓					
Bioengineering for improved functionality	Food crops with RSFR properties			✓		✓	✓					
Bioengineering for improved functionality	Inorganic fertilizers	✓		✓				✓	✓			
New planting and production techniques with sustainable resources and materials	Use of halophyte plants to provide seawater irrigation and use of saline aquifers; genomics can play a role in enhancing halophyte water desalination efficiency	✓	✓	✓		✓	✓	✓	✓			
New planting and production techniques with sustainable resources and materials	Local crop generation to meet local demand offers the greatest use of next-generation technologies to sustain the environment			✓		✓	✓					
Nutrigenomics												
Proteomic combinations for better health	Customization of foods based on nutrition/dietary needs	✓	✓	✓	✓	✓	✓	✓			✓	✓
Proteomic combinations for better health	Customization of foods to help treat chronic, sub-acute, and acute diseases/infections (e.g. cancers, type-2 diabetes, Chrons disease, high blood pressure, flu, and rashes)	✓	✓	✓	✓	✓	✓	✓			✓	✓
Food supply chain information systems												
Bioinformatics systems and solutions	Bioinformatics for DNA matrix arrays containing annotated sequences and linkage/hybrid maps and other genetic makeup data			✓	✓	✓	✓				✓	✓
Supply chain technology infrastructure and monitoring tools	ICTs - Information Communication Technologies that link the field to the check out lane for food and animal products							✓	✓		✓	✓
Supply chain technology infrastructure and monitoring tools	Virtual Enterprise Networks - connections between industry, academic, and government research resources							✓	✓		✓	✓
Supply chain technology infrastructure and monitoring tools	Collaborative design technologies for use with food and animal product manufacturers, food packaging manufacturers, and distributors							✓			✓	✓
Supply chain technology infrastructure and monitoring tools	Supply chain integration with regulatory agencies to accelerate containment of recalled food and animal products							✓		✓	✓	✓
Food safety / biological containment												
Food safety systems, technology, and monitoring tools	Biosensors integration within the food supply chain monitoring for changes to safety of food and animal resources, products, and sharing of food safety leading practices	✓	✓	✓		✓	✓	✓			✓	✓

Technologies	Products	Catalysis	Synthesis	Bioengineering	Clinical capabilities	Systems biology	Genomics and proteomics	Nanotechnology	Materials science	Imaging/ navigation	Computer science	Data management and analysis
Food safety systems, technology, and monitoring tools	Biological containment systems for isolating contaminated food crops and animals and to prevent crossbreeding/pollination of genetically modified food crops and animals						✓	✓	✓		✓	✓
Food safety systems, technology, and monitoring tools	Rapid and efficient transcriptomics, proteomics, and biosensor-based technologies are in development for detecting a wide variety of contaminants	✓	✓	✓		✓	✓	✓			✓	✓
Nanotechnology												
Packaging utilizing nanotech and materials science	Multi-functional packaging (keeps food cold without freezing or packaging adhering to product)	✓	✓				✓	✓	✓			
Packaging utilizing nanotech and materials science	Anti-microbial packaging designed to seek and destroy food contaminants and microorganisms	✓	✓				✓	✓	✓		✓	✓
Food protection additives using nanotech and materials science	Nanosensor materials that detect toxins, chemicals, and pathogens and alert consumer to their contents prior to exposure	✓	✓	✓			✓	✓	✓	✓	✓	✓
Food protection additives using nanotech and materials science	Nanocoatings designed to serve as repellents to dirt, fungi, and other unwanted product contaminants							✓	✓		✓	✓
Packaging utilizing nanotech and materials science	Nanotubes, nanowheels, nanofibers can be used to ensure efficient breakdown of packaging material for recycling/recombination							✓	✓		✓	✓
Green chemistry												
Packaging utilizing nanotech and materials science	Reduction or elimination of hazardous substances using advanced polymeric materials in food packaging; biopolymers, nanotechnology and nanocomposites, and active and intelligent packaging properties are all potential green chemistry packaging materials	✓	✓	✓			✓	✓	✓		✓	✓
Packaging utilizing nanotech and materials science	Biological-based materials with nanotechnology would provide products for flexible and rigid packaging sectors	✓	✓				✓	✓	✓			
Non-thermal food processing												
Sterilization from radiation, electricity, magnetic, or carbon dioxide-based food processing technologies	Ionizing radiation from pulsed x-rays, pulsed light and electric fields, high-voltage arc discharge, magnetic fields, dense phase carbon dioxide (CO_2)						✓	✓		✓	✓	✓
Sterilization from nanotech and materials science food processing technologies	Hurdle technologies that include new packaging materials	✓	✓	✓			✓	✓			✓	✓
Resource purification												
Purification technologies improving availability of sustainable resources with minimal by-products	Disinfection of water to remove low-concentration contaminants and provide ability to re-use waste water with minimal toxic by-products; use of photons and engineered nanostructures, and microorganism-based technologies	✓	✓					✓	✓			
Drug / biological treatment delivery												
Food products capable of drug/biological treatment delivery	Foods designed for drug/biologic delivery	✓	✓	✓	✓		✓	✓			✓	
Food products capable of drug/biological treatment delivery	Snacks to be taken over several days to release the correct drug dosage	✓	✓	✓	✓		✓	✓			✓	
Basic ingredients and additives used to deliver drug and biological treatments	Basic ingredients and food additives designed to be cooked with/ combined with other foods to release the correct drug dosage over several days	✓	✓	✓	✓		✓	✓			✓	
High nutrition and environmentally sustainable food products												
Proteomic combinations for better health	Organic food and animal products from local sources that contain nutritional elements based on specific dietary needs					✓	✓				✓	✓
Proteomic combinations for better health	Genetically modified food and animal products that contain high-nutrient levels from high-efficiency crop yields and livestock		✓	✓		✓	✓	✓			✓	✓

This section applied the Strategic Flexibility Framework and presented an unconstrained exploration of opportunities in the food industry. The result is a portfolio of technologies, products, and knowledge clusters relevant across a range of scenarios. Decision makers can develop these knowledge clusters to improve the competitive position of their organizations.

4.0 Next steps

The analysis of technologies, products, and knowledge clusters, combined with the opportunities identified in the broad exploration of the future, is useful in two ways.

One application is for regional industry decision makers in academia, government, and industry, who can match these opportunities with their regional strengths and develop a local vision to take advantage of these opportunities. Based on our findings, and on an analysis of regional competitive position, decision makers can develop high-level recommendations to build the regional industry's foundational capabilities through policy, infrastructure, and education initiatives. More detailed analyses can be conducted to create entity-specific strategies or local economic development plans.

Another application is a more constrained execution of the Strategic Flexibility Framework to determine entity-specific strategies and to plan for the future. Specific entities can build on this analysis and create initiatives in corporate strategy that can accelerate innovation and growth as well as inform business development activities. For example, an industry decision maker can use the process to reconfigure an in-house strategic investment portfolio. Similarly, a university can use the framework to reconfigure its research funding portfolio and more firmly determine which core investments should be made and which contingent investments can create options if pursued partially or in partnership with other entities. Likewise, a state government can use the framework to create new economic development initiatives, identifying core technologies that require investments for creating knowledge clusters in public universities or for building basic science concepts in K-12 education.

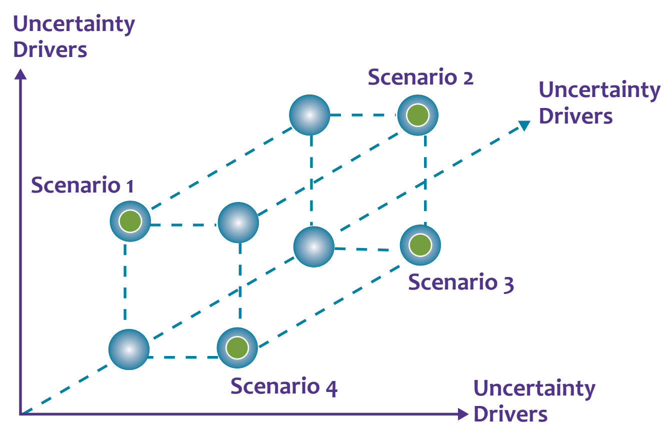
Constrained entity-specific application of the Strategic Flexibility Framework

The following is an example of the application of the Strategic Flexibility Framework executed for specific entities.

1. Create scenarios

The first step in applying this framework to a single entity for a particular strategic decision is to create scenarios for the relevant range of strategic uncertainty. As in the above unconstrained scenario-building exercise, drivers of change are defined and vetted in order to fully capture uncertainty along several dimensions. Scenarios that represent possible futures based on these drivers are then developed.

Figure 7: Creating scenarios



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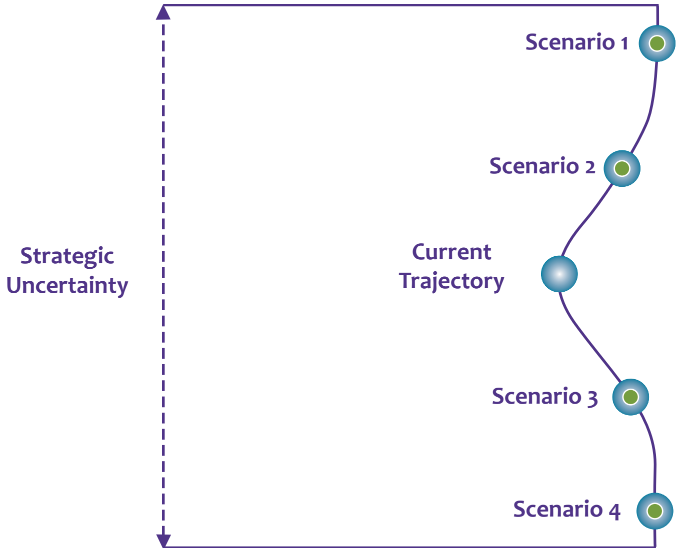
2. Choose strategies

The second step is to choose strategies representing a range of strategic uncertainty relevant to the particular industry.

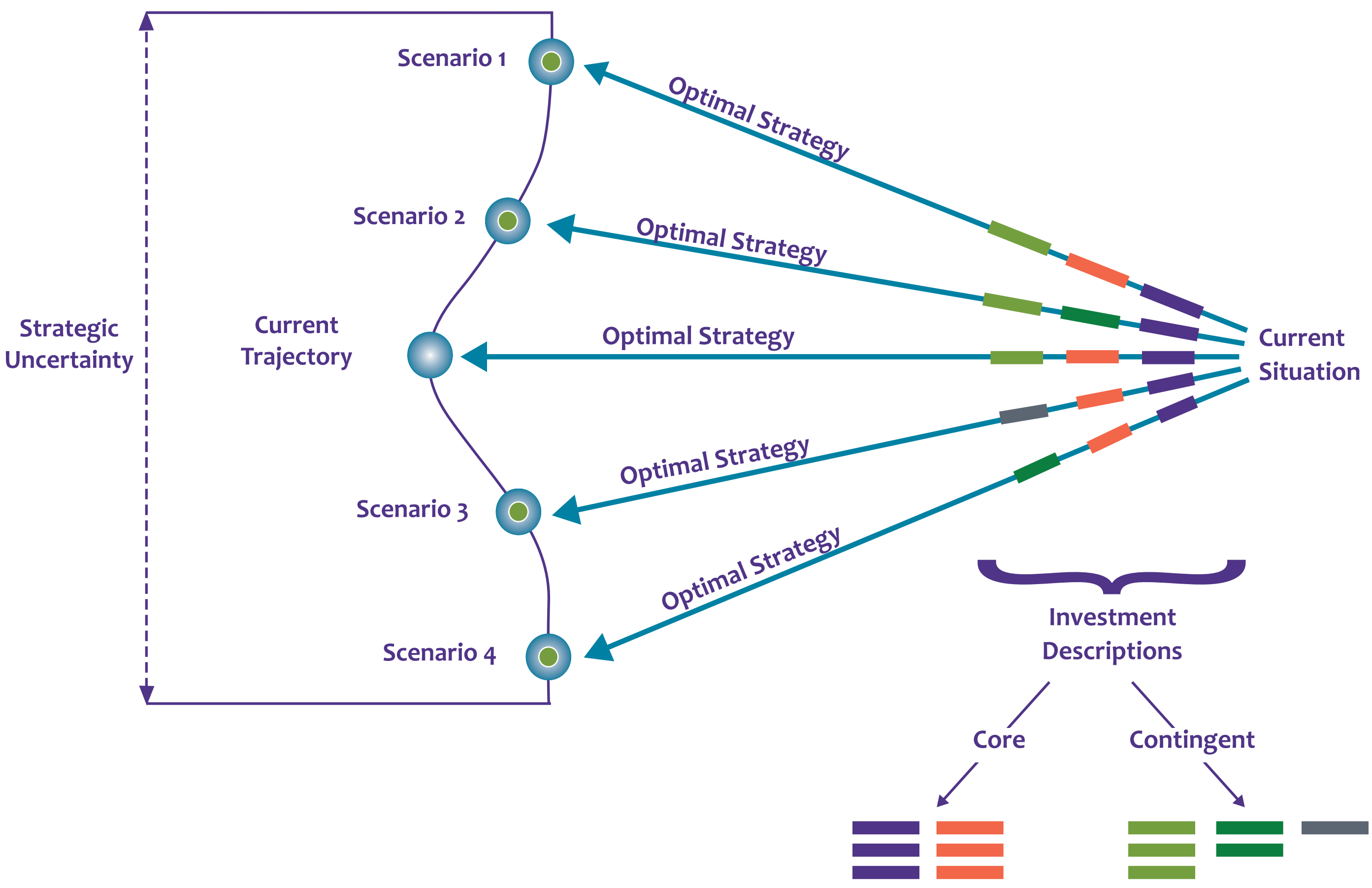
Figure 8: Range of strategic uncertainty



3. Identify optimal strategies

Next, optimal strategies for each scenario within this range are created. Investments needed to attain optimal strategies for every scenario are identified. Different investments can then be categorized as either core or contingent.

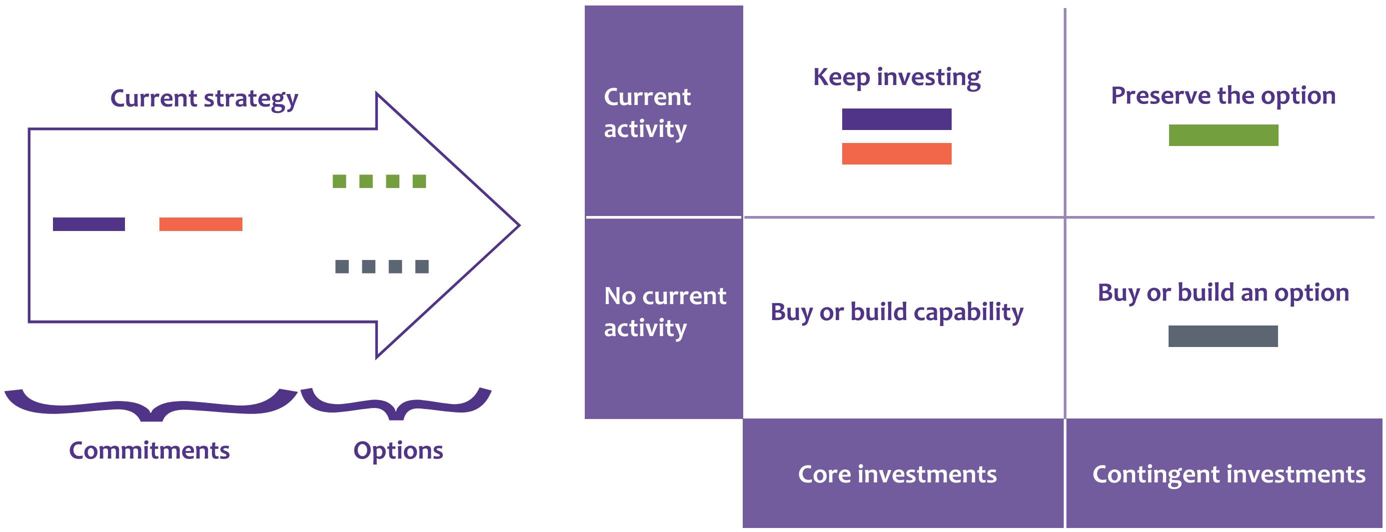
Figure 9: Identify optimal strategies



4. Compare to current strategy

The fourth step is to compare the investment decisions on the current trajectory with those chosen for each optimal strategy.

Figure 10: Compare investment decisions to current trajectory



5. Add detailed definitions

The fifth step is to add detailed definitions of each optimal strategy along with descriptions of the types of risk associated with each investment. For example, Figure 11 below illustrates a potential set of investment options and their associated levels of risk. This is intended only as an illustration, and is not based on actual data.

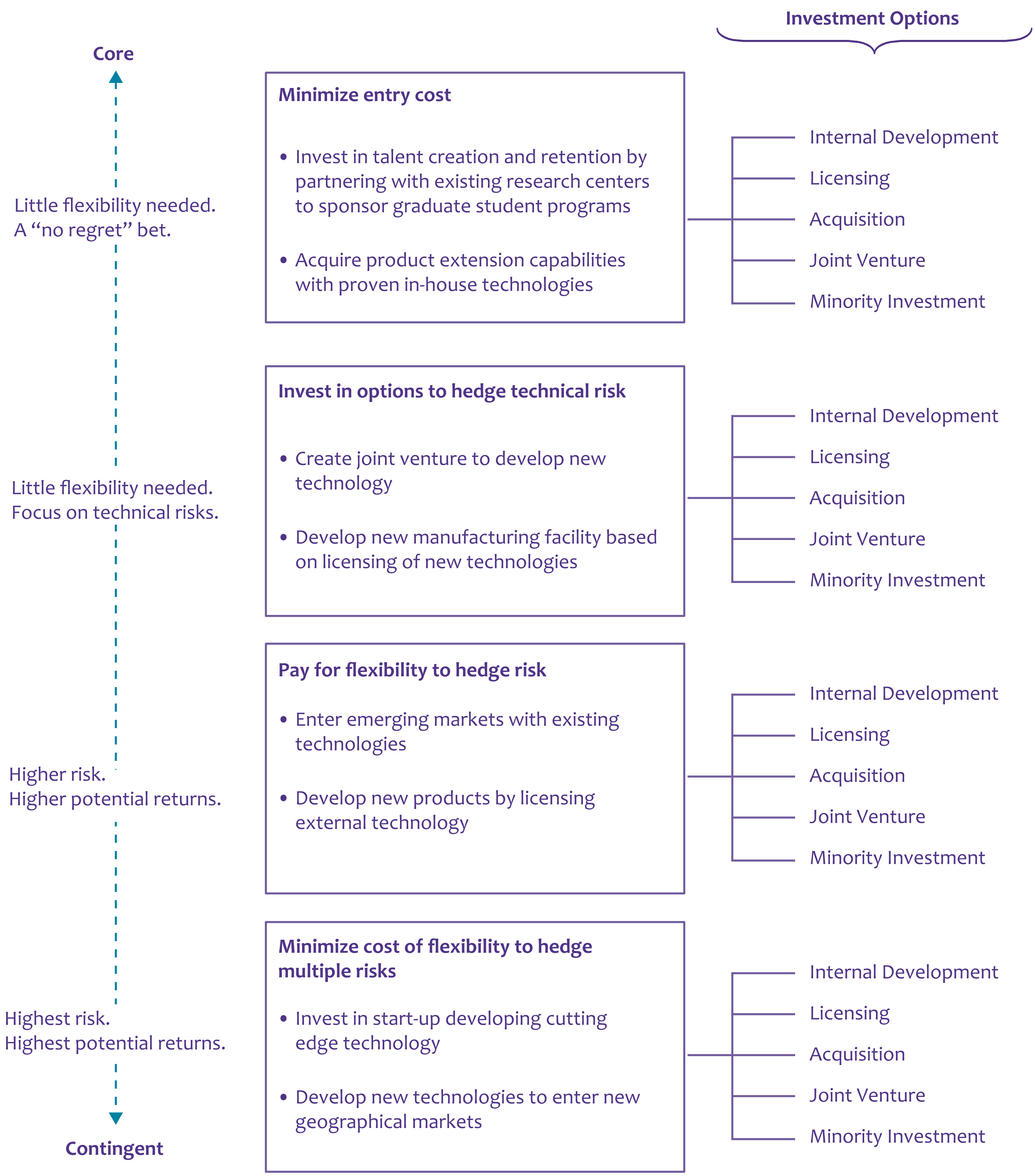
Figure 11: Optimal strategy definitions by risk type

Technical risk	Commercial risk: Low	Commercial risk: High
High	• Create joint venture to develop new technology • Develop new manufacturing facility based on licensing of new technologies	• Invest in start-up developing cutting edge technology • Develop new technologies to enter new geographical markets
Low	• Invest in talent creation and retention by partnering with existing research centers to sponsor graduate student programs • Acquire product extension capabilities with proven in-house technologies	• Enter emerging markets with existing technologies • Develop new products by licensing external technology

6. Launch business development analyses

Next, business development analyses are conducted to quantify investment costs and assess the various investment options available. These options are to be managed and revised based on changing industry dynamics along with the decision maker's constraints, investment capacity, and risk appetite.

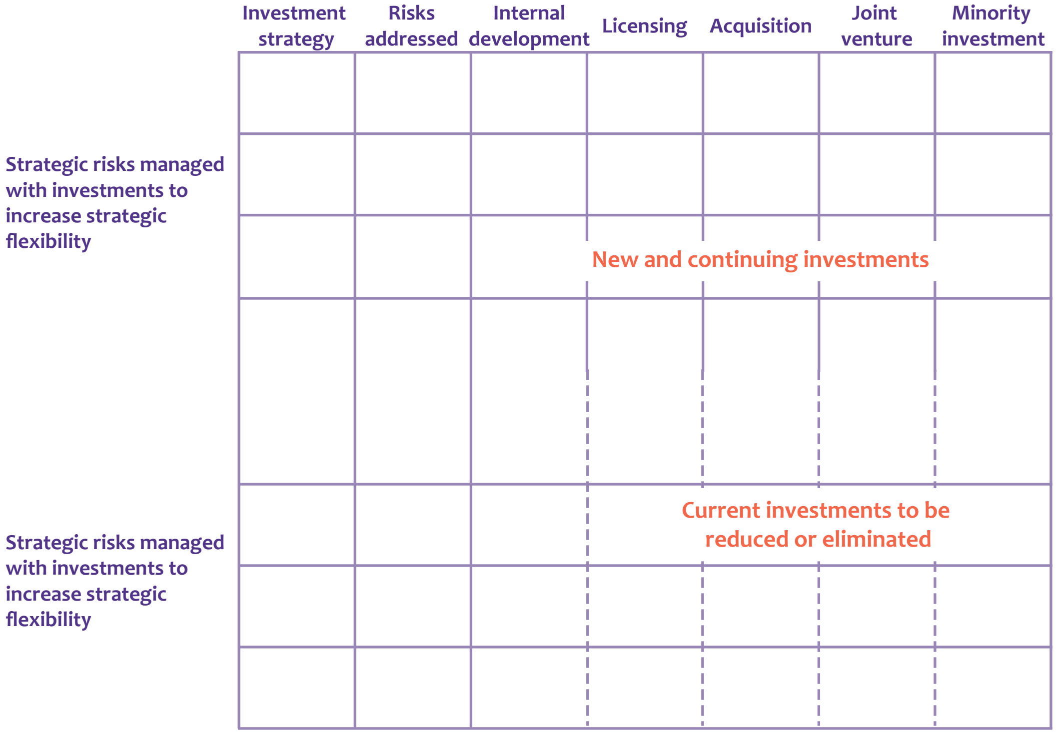
Figure 12: Business development analyses



7. Construct portfolio

Finally, a quantified portfolio is constructed based on the investment options, taking into account the available budget and risk tolerance. These strategic flexibility investments are then incorporated into the strategic plan of the single entity.

Figure 13: Construct quantified portfolio



Next steps for regional industry stakeholders

The research, scenarios, and findings in these papers were developed for a very specific purpose: to assist BBAM define a set of core and contingent strategies for Destination 2025.

Decision makers can use the findings of this paper in several ways. Decision makers in academia can use the portfolio of technologies and products identified to analyze their research portfolio and reconfigure it. They can also build knowledge clusters to develop their academic and research programs.

Decision makers in industry can use the findings of this paper to identify opportunities presented by emerging technologies and market trends. They can develop technologies and products by acquiring relevant expertise or conducting in-house research. Decision makers in industry can also develop specific strategies by applying their resource constraints to a selected range of opportunities identified in this paper.

Decision makers in government can use the opportunities identified in this paper to develop the competitiveness of the regional industry and with it attract regional human capital, investments, and new businesses. Government can develop policies and invest in education and infrastructure to improve the competitiveness of the regional industry. Collectively, the findings of this paper can be used to develop a vision for the future of a regional industry with specific recommendations for policy, education, and infrastructure development.

The interpretation of the findings and potential next steps identified in this paper will vary according to the reader's current position, objectives, and constraints. For Minnesota stakeholders, use of these materials should be undertaken with the guidance of BBAM in their role to facilitate the implementation of Destination 2025 strategies in the state of Minnesota. BBAM and Deloitte Consulting LLP are not responsible for any actions taken by anyone based on the content of this report.

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Destination 2025

A collaboration between The BioBusiness Alliance of Minnesota and Deloitte Consulting LLP

Destination 2025 is an initiative of The BioBusiness Alliance of Minnesota in collaboration with Deloitte Consulting LLP to develop a roadmap for the bioscience markets in Minnesota for the next 20 years. The Destination 2025 project examines six markets of the bioscience industry: Animal Health, Food, Medical Devices, Biologics and Biopharmaceuticals, Renewable Materials, and Renewable Energy.