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# Position Statement on Food Security and Safety

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Society for General Microbiology
Marlborough House
Basingstoke Road
Spencers Wood
Reading RG7 1AG
UK

Tel. 0118 988 1819
Email pa@sgm.ac.uk
Web www.sgm.ac.uk



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Front cover: Leaf infected with rust fungus *Eye of Science / Science Photo Library*
Background *iStockphoto*

# Foreword

The global challenges we face are now well known and acknowledged. Many stem from the fact that there are 7 billion people on our planet today, but in fewer than four decades there will be 9 billion. This leads in particular to the challenge of global food security. In parts of the world there is already a food security crisis, but with more people, less land and fewer inputs we have to find a way to give the growing global population access to safe, nutritious and affordable food.

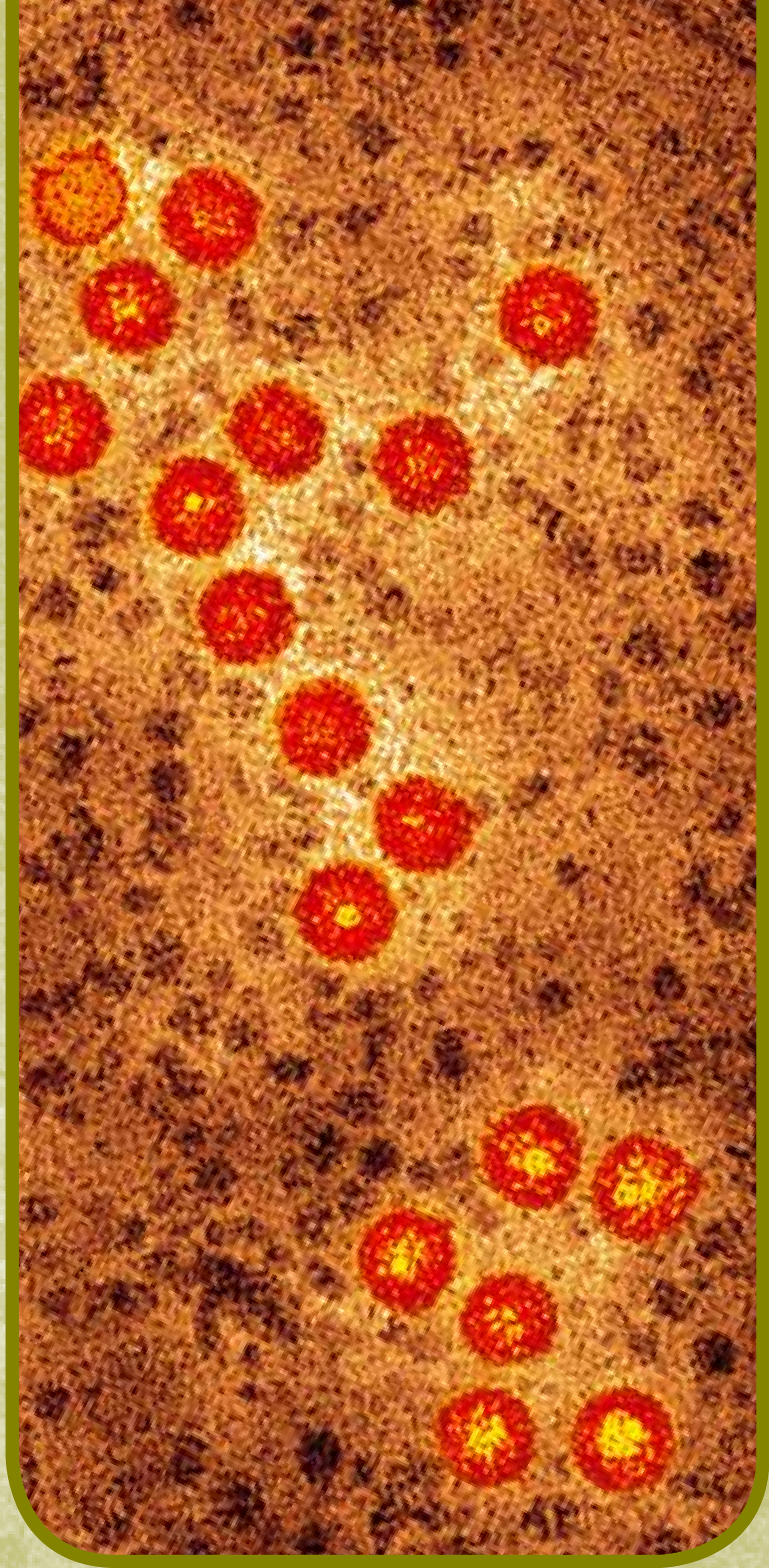
The challenge is multi-faceted: we need to produce enough of the right food of the right quality, transport it, trade it, prevent waste and ensure it is safe. There will be no one solution to the food security challenge. It demands a broad-spectrum approach, and microbiology has a key and central role to play in this.

Every part of the microbiology research community has something to contribute. Microbes are ubiquitous – from our guts to the air, water and soil. This, together with the threats they pose and the services they provide, makes the study of microbes vital. Such studies will include ensuring food safety through tackling pathogens such as *Campylobacter*, *Escherichia coli* and rotaviruses in the food chain, fostering a better understand of nutrient cycling in soil, reducing losses to fungal and bacterial plant and animal pathogens, and helping to further our understanding of the symbiotic relationships that are essential to so many of our crops. Of course, fungi and algae are already consumed directly, as mushrooms, mycoprotein and seaweeds, many 'preserved' foods are the products of microbial fermentations, and microbes contribute important elements of the food chain that end for us in organisms such as fish.

BBSRC, and our partners in the multi-funder Global Food Security programme, recognize the role of microbiology in supporting efforts to meet this important challenge. We have demonstrated this through our support for programmes that have major microbiology elements and look forward to working closely with the strong UK microbiology community.

I commend the Society for General Microbiology for their work on this position statement and give it my full support.

*Professor Douglas Kell, Chief Executive, Biotechnology and Biological Sciences Research Council (BBSRC)*



Virus particles infecting sugar beet. *Rothamsted Research/SPL*

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# Executive summary – key conclusions for policy-makers

Microbiological research has been and continues to be central to meeting the global challenges of food security and food safety, defined by the Food and Agriculture Organization [1] as '*when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life*'.

With the world's population predicted to rise from its current 7 billion to 9 billion by 2050, producing enough food to feed this expanding population has been recognized as one of the greatest challenges facing mankind. In 2011, a major 2-year study from the UK Government Office for Science 'Foresight' programme *The Future of Food and Farming* [2] was published, outlining the emerging issues and challenges to global food security and safety. A number of action plans to meet this challenge have been published by the relevant global agencies, including UK government departments, research councils, the Royal Society and others [3, 4, 5, 6, 7].

The Society for General Microbiology (SGM) in partnership with other leading microbiology and microbiology-related organizations, the Society for Applied Microbiology, the British Mycological Society and the British Society for Plant Pathology, is concerned that the role of microbiology in meeting these challenges is poorly understood and under-represented at a time when funding for universities and institutes has been cut, leading to a shortage of expertise in many important microbiology disciplines across the UK [6].

Food security is not just about increasing food productivity; it is also about wasting less. Furthermore, supplying safe, nutritious foods must be achieved in a sustainable manner with minimal impact on the environment and animal welfare. Meeting the challenges is exacerbated by a number of key drivers and constraints, including climate change, energy usage, mineral and water availability and population dynamics, and to be sustainable must occur within the '*safe operating space for humanity*' identified by Rockström *et al.* [8].

Microbes (bacteria, fungi, viruses, protozoa, algae and archaea) and their activities are involved at every step of the food chain. Understanding the role of microbes at all steps in the process of plant and animal production, soil and water management, and harvesting, storage and processing of agricultural products is necessary. Now and in the future, microbiological research and development will play a profoundly important role in sustaining and improving food production, food safety, and environmental quality while reducing waste.

Critically, investment in microbiological research and development to tackle food security and safety will have measurable socio-economic benefits. For example, for every 1% reduction in crop pests and diseases it has been estimated that an extra 25 million people could be fed [9], and for each 1% reduction in the overall incidence of UK food-borne disease it has been estimated that there would be around 10,000 fewer cases each year; this 1% represents an economic saving of around £20 million [15].

History records that microbiological research has delivered major advances in food security and safety. Important milestones include:

- Identification and application of safe processes for food preservation, such as canning and pasteurization, and understanding the biology of pathogenic and spoilage microbes to reduce their transmission in the food chain, leading to developments of safer foods with a longer shelf life.
- Exploiting antimicrobial substances produced by naturally occurring microbes as weapons against plant and animal pathogens.
- Vaccine development to improve the health of livestock and reduce transmission of animal pathogens to humans.
- Producing novel food products, including probiotics and nutritionally enhanced food through fermentation.
- Exploiting microbial processes to manage or reduce waste.

It needs to be recognized that there are key overarching factors which impact on microbiological activity, including:

- Microbes do not respect international boundaries and consequently food-borne pathogens, and also animal and plant diseases, such as foot-and-mouth disease, classical swine fever, coffee leaf rust and soybean rust, can be spread rapidly worldwide via trade, travel or arthropod vectors, depending on the pathogen, to new geographical areas. Moreover some microbes move between animals and humans, introducing diseases and resistances to antibiotics.
- In their natural habitat, microbes live in diverse, complex, interdependent communities, the ecology of which must be fully understood if we are to eradicate disease and exploit the beneficial role that microbes play in achieving food security.
- Many microbes have the capacity to evolve rapidly to become better suited to *their* environment, not necessarily to our benefit, thereby changing their behaviour and meaning that continual vigilance is required. Such evolution can allow microbes to escape control by drugs or vaccines, meaning that diseases that were once considered under control may re-emerge.

Nine research themes have been identified where the role of microbiological research is crucial to help meet the challenges of ensuing global food security and safety.

## Research themes

Within this Executive Summary, just two areas of necessary research are identified for each theme. The full report provides a more detailed set.

### 1. Soil health and nutrient cycling

The soil microbial community is largely uncharacterized, but is responsible for decomposition of organic material and biogeochemical cycling to provide plant nutrients, capture and release of essential minerals, and maintenance of soil structure. Microbial respiration of nitrate is estimated to account for as much as one-third of the loss of fertilizer or other nitrogen sources from soil-containing plants [11]. Further research into the soil community and role in nutrient cycling will allow optimization of nutrient yield, for example research to:

- Understand the role of microbes in nutrient cycling, particularly phosphate, nitrogen and micronutrient metals.
- Determine the effect of external factors on soil microbial communities and their functions, such as decomposition and nutrient cycling.

### 2. Plant–microbe dynamics

Microbial interactions with plants can be beneficial (for example nitrogen fixation or mineral uptake in root systems), parasitic or pathogenic. Microbes can switch between beneficial, parasitic and pathogenic stages during their life-cycles; understanding these change triggers is essential for controlling pathogens and enhancing beneficial interactions to maximize crop yields in a sustainable way. Research is needed to:

- Enhance beneficial (for example mycorrhizal, rhizobial or endophyte) plant–microbe rhizosphere (volume of soil around the plant roots) and phyllosphere (leaf surface habitat for microbes) interactions to enhance nutrient uptake and stress tolerance.
- Understand and exploit the triggers that change microbes between beneficial, parasitic and pathogenic stages of their life-cycles as a means to identify durable crop resistance and better target crop protection.

### 3. Crop pathogens

Pests and diseases can considerably decrease crop production with current losses, estimated to be more than £150bn worldwide [12], contributing to global food insecurity. There are opportunities to exploit new methods and models to decrease disease-induced crop losses. Research is needed to:

- Identify crop resistance against pathogens that is durable through exploitation of new crop and pathogen genomic data, and new understanding of factors affecting severity of epidemics.
- Guide government/industry strategies by exploiting new models to predict impacts of changes in climate and agricultural practices on severity of crop diseases.

## 4. Gut microbiology in farm animals

The complex population of micro-organisms in the gut of farm animals plays an important role in the nutrition and health of the animal. In sheep and cattle, microbes are responsible for conversion of plant material into energy and protein to support meat and milk production, but also production of methane, a potent greenhouse gas. In pigs and poultry the gut microbes play a key role in digestive efficiency and in preventing the passage of pathogens. Research is needed to:

- Develop novel methods to modify the gut microbial population in beneficial ways, for example to improve energy retention from the diet and to decrease the production of greenhouse gases from farmed livestock.
- Understand how indigenous microflora in the gut protects against invading microbes.

## 5. Animal pathogens

Infectious diseases of food-producing animals result in reduced efficiency or significant losses in food production from animals and adversely affect animal welfare and trade. With nearly 700 million of the world's poorest people relying on farming animals for their survival [13], effective control of animal pathogens is crucial not only for safeguarding and securing national and international food supplies, but also for alleviating rural poverty in developing countries. Research is needed to:

- Develop novel and improved rapid diagnostic tests, including simple on-farm tests, in order to detect outbreaks early enough to effect containment (c.f. 2001 UK foot-and-mouth disease outbreak).
- Develop effective control measures, such as new antimicrobial compounds and novel or improved vaccines that induce long-lived immunity and/or which protect against multiple strains of the same pathogen.

## 6. Food spoilage

Food spoilage may be defined as any change that renders food unfit or unsafe for human consumption. Microbiological spoilage is a significant problem with respect to the shelf life of raw and processed foods (meat, fish and vegetable products) and is a key contributor to food waste. Future food security will necessitate that less food is wasted. Research into optimal storage and transport conditions, methods of food preservation and reduction in microbial contaminants will contribute significantly to the amount of food available, particularly in the developing world. Research is needed to:

- Understand the microbial ecology of pre- and post-harvest produce, and how these microbial populations can affect shelf life and food quality.
- Develop rapid diagnostics to allow for correct species and strain identification from within mixed microbial communities and understand the food source attribution of microbes.

## 7. Food safety and human diseases

Sustainable production of safe and nutritious food requires improvements in food safety. Of 335 emerging infectious diseases over the last 70 years, 60% have been acquired through animals (note that 60% relates to all zoonoses and not just food-borne ones) [14]; intensive agriculture increases opportunities for evolution and spread of harmful microbes. Food-borne illness is a global burden. In the UK, it is estimated that about 1 million people suffer a food-borne illness of which 20,000 receive hospital treatment, and there are over 500 deaths. This cost to the UK economy in 2009 was about £2bn [15]. Research is required to mitigate this:

- To better understand the microbes, their hosts, environmental factors and the interactions between them that result in transmission of pathogens in the food chain and subsequently to food-borne disease.
- To develop strategies that reduce transmission throughout the food chain, infection and disease using appropriate research models, and to predict the zoonotic and epidemic potential of microbes found in animals by exploiting state-of-the-art technologies.

## 8. Waste reduction and management

More than half of the food grown is discarded before or after it reaches consumers and over one-third of landfill waste in the UK comes from the food sector. Such landfill releases greenhouse gases, particularly methane. The core microbiological challenges of waste management concern optimization and matching of microbial processes to specific waste streams. In particular, research into controlled anaerobic digestion is required to understand this process and convert waste into usable energy and fertilizer. For example, research is needed to:

- Understand how the microbial community in anaerobic digesters can be optimized.
- Improve production of cell-wall-degrading enzymes from microbial sources for the commercial breakdown of plant structures.

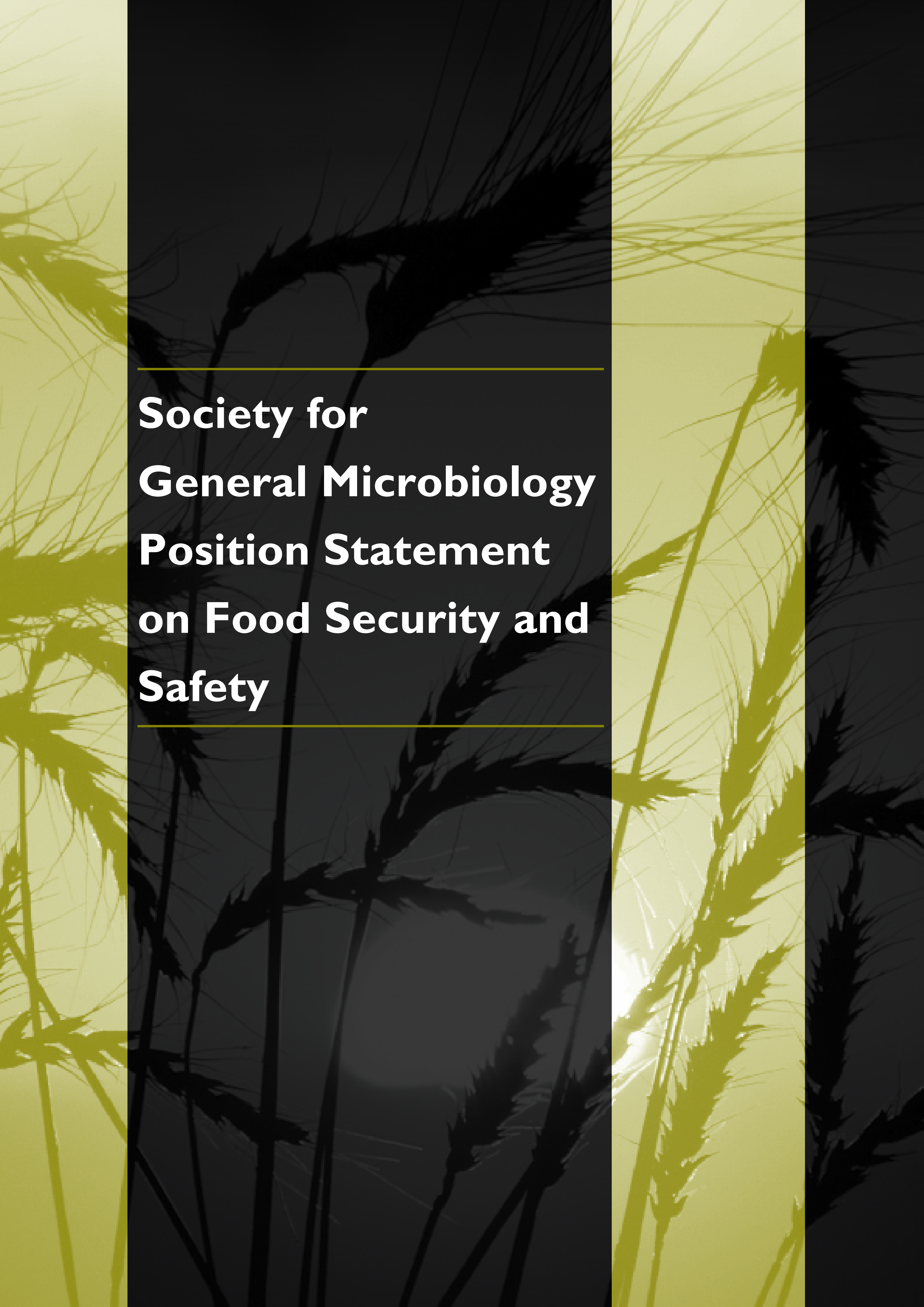
## 9. Novel methods

The vast majority of micro-organisms – whether beneficial, harmful or neither – remain to be discovered. Even the presence or absence of organisms we know may be difficult to determine. Research needs to focus on new identification techniques and accurate data acquisition to unravel the complexity of microbial communities involved in the production and utilization of food and for increased tracing of microbes through the food chain. For example, research is needed to:

- Develop data management systems that are capable of collecting, storing, analysing and communicating data.
- Develop methods to study unculturable microbes, which are becoming increasingly implicated in disease and environmental functions such as nutrient cycling especially in soil, and to trace pathogenic and spoilage microbes through the food chain.

The SGM recognizes that any proposed solutions to the challenges of food security and safety will require multidisciplinary, multinational teams to effectively meet the global challenges of our future food supply. However, to deliver potential solutions to this global issue, funds need to be committed to:

- Support microbiology research programmes and to procure the necessary resources required to deliver the proposed research.
- Support the training and development of skilled microbiologists.
- Provide world-class research facilities, including those needed to study microbes in the animal, crop or environmental systems where they act rather than surrogate laboratory-based models.



# Society for General Microbiology Position Statement on Food Security and Safety

Diseased cocoa pods. *USDA/ARS*

# Introduction

Microbiological research has been and continues to be central to meeting the global challenges of food security and food safety, defined by the Food and Agriculture Organization [1] as '*when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life*'. However, meeting the challenges of our future food supply is exacerbated by key drivers and constraints, including:

- Population dynamics
- Climate change
- Energy usage
- Mineral availability
- Water availability
- Globalization

The world's population is currently 7 billion, of whom approximately 900 million people are food-insecure. The population is set to exceed 9 billion by 2050 and demand for food is likely to increase further because of growing affluence and urbanization. Achieving sustainable supplies of safe, nutritious foods with minimal impact on the environment and animal welfare is therefore vital. To achieve sustainable agriculture, the issues of maintaining biodiversity and ecosystem services have to be addressed alongside increasing food production. However, food security is not just about increasing food productivity; it's also about wasting less. The UN estimates global harvests and food chain losses – before even reaching the shop shelves – at around 1,400 calories per person, per day [7]. More than 25% of the food that is bought is not consumed; instead, it is wasted because of delays in the food chain, poor storage and human behaviour [16].

In 2011, a major 2-year study from the UK Government Office for Science 'Foresight' programme *The Future of Food and Farming* [2] was published outlining the emerging issues and challenges to global food security and safety. The Society for General Microbiology (SGM) in partnership with other leading microbiology and microbiology related organizations, the Society for Applied Microbiology, the British Mycological Society and the British Society for Plant Pathology, is concerned that the role of microbiology in meeting these challenges is poorly understood and under-represented at a time when funding for universities and institutes has been cut leading to a shortage of expertise, in many important microbiology disciplines, across the UK [6].

History records that microbiological research has delivered major advances in food security and safety. Important milestones include:

- Identification and application of safe processes for food preservation, such as canning and pasteurization, and understanding the biology of pathogenic and spoilage microbes to reduce their transmission in the food chain, leading to developments of safer foods with a longer shelf life.
- Exploiting antimicrobial substances produced by naturally occurring microbes as weapons against plant and animal pathogens.
- Vaccine development to improve the health of livestock and reduce transmission of animal pathogens to humans.
- Producing novel food products, including probiotics and nutritionally enhanced food through fermentation.
- Exploiting microbial processes to manage or reduce waste.

Now, and in the future, microbiology research and development will play a profoundly important role in sustaining and improving food production, food safety and environmental quality while reducing waste. Understanding the activities of microbes at all steps in the process of plant and animal production, soil and water management, and the harvesting, storage and processing of agricultural products is necessary. Microbial communities play a key role in maintaining soil health and productivity, in the fermentation and degradation of plant biomass material to produce both food and fuel, and in the production of novel foods and feeds. Microbial communities also promote and maintain gut health in animals. The introduction of 'omic technologies have enabled the experimental study of such communities previously not achievable. For example, intervention strategies may have unforeseen consequences, such as knock-on effects of manipulation of one microbe on the behaviour of the community as a whole, and it is now possible to explore this experimentally and in detail.

Improvements in food security will bring significant socioeconomic benefits. For every 1% reduction in crop pests and diseases it has been estimated that an extra 25 million people potentially could be fed [9]. Livestock contribute significantly to the livelihoods of nearly 700 million of the world's poor [13]; therefore, improvements to animal health via the provision of new vaccines and antibiotics have the potential to alleviate poverty substantially, as evidenced by the recent eradication of rinderpest, which is estimated to have saved the African economy US$1bn per annum [17]. Moreover, animals are recognized as the principle source of new diseases affecting humans. A recent study shows that over 60% of 335 emerging infectious diseases in humans from the last seven decades are zoonoses [14], and intensification of animal and crop production will increase opportunities for the evolution and spread of harmful microbes. An understanding of the activities of microbes in food animals and crops, and of the traits that allow them to infect humans, is therefore vital to improve food safety.

It needs to be recognized that there are key overarching factors which impact on microbiological activity, including:

- Microbes do not respect international boundaries and consequently food-borne pathogens, and also animal and plant diseases, such as foot-and-mouth disease, classical swine fever, coffee leaf rust and soybean rust, can be spread rapidly worldwide via trade, travel or arthropod vectors, depending on the pathogen, to new geographical areas. Moreover some microbes move between animals and humans, introducing diseases and resistances to antibiotics.
- In their natural habitat, microbes live in diverse, complex, interdependent communities, the ecology of which must be fully understood if we are to eradicate disease and exploit the beneficial role that microbes play in achieving food security.
- Many microbes have the capacity to evolve rapidly to become better suited to *their* environment, not necessarily to our benefit, thereby changing their behaviour and meaning that continual vigilance is required. Such evolution can allow microbes to escape control by drugs or vaccines, meaning that diseases that were once considered under control may re-emerge.

To maximize the benefit of any research it must be possible for microbiologists to carry out their research in target animals or crops, with less reliance on surrogate rodent- and cell-based assays, despite the high cost of contained accommodation for such work.

Stem rust on wheat. *USDA/ARS*

# Drivers and constraints

The main drivers and constraints underlying food insecurity and safety are:

**Population dynamics.** A rising population and an increasing move towards urbanization will affect land usage and erosion. Emerging economies have increasing levels of disposable income, resulting in changing food consumption patterns and, in particular, an increasing consumption of animal, including fish, protein. Studies have predicted a global increase in the consumption of meat (annual per capita meat consumption) in developing countries from 28 kg in 2002 to 37 kg in 2030 and in developed countries from 78 kg in 2002 to 89 kg in 2030 [18], placing a heavy burden on livestock and aquatic organism production. The increased globalization of trade and people may lead to exposure to new pathogens and to the emergence of new pathogens. There is also the need to provide food to a higher safety specification for an increasing number of susceptible individuals (such as the elderly and immunocompromised).

**Climate change.** Climate change will affect food security through its impact on all components of the food system process along the food chain. Mitigating climate change requires that we reduce agricultural greenhouse gas emissions and this means that those involved in food production will need to adopt good working practices for mitigating climate change. There are concerns that some of the effects of climate change will increase the global burden of disease in crops and animals, including humans, and to diseases becoming prevalent in parts of the world where they are currently only a minor issue or not an issue at all. Further work needs to be done to model the effects of predicted 21st century climate change on disease epidemics. For example, warming of European countries has seen the emergence of bluetongue in livestock owing to changes in distribution of the insect vector. Patterns of food spoilage may also be affected by climate change too.

**Energy usage.** Farming in developed countries is not sustainable without mineral fertilizers, and the energy to make these contributes to a crop's carbon footprint. For example, manufacture of nitrogen fertilizers uses about 5% of the world's natural gas production; this is equivalent approximately 1.2% of the world's total annual energy consumption [19].

**Mineral availability.** Some mineral resources are limited. For example, reserves of phosphate (a key nutrient for plant growth) are predicted, under current conditions, to last for approximately only 125 years. However, it has also been predicted that clean phosphate rock will run out in approximately 50 years if growth remains at 3% [20]. There are no substitutes for phosphate in agriculture and phosphorous will need to be recovered and reused, or methods found to make the considerable amounts of phosphate present in soil bioavailable.

**Water availability.** Less than 1% of the world's water is fresh [21], and 70% of that fresh water is used for food production [22]. This means that water will become a critical factor in the future, so new ways need to be found to make more efficient use of the available fresh water, while ensuring its quality.

**Globalization.** This can be defined as the spread and connectedness of production, communication and technologies across the world. It leads to increased integration and interdependency between countries.

# Research themes

Nine research themes have been identified where the role of microbiological research is crucial to help meet the challenges of ensuing global food security and safety.

For each of the nine research themes, the SGM has summarized **core challenges** that arise from some of the **main drivers** underpinning the goal of ensuring food security and safety. From these core challenges **key research priorities** have been identified. The SGM recognizes that any proposed solutions to food security and safety will require multidisciplinary, multinational teams to effectively meet the global challenges of our future food supply. Funds need to be committed to support microbiology research programmes, which have the potential to deliver solutions to these global challenges.

## 1. Soil health and nutrient cycling

The potential of plants to achieve their theoretical experimental yields is critically dependent upon the potential of the soil in which they are grown. Healthy soils contain a high abundance of diverse micro-organisms ($10^9$–$10^{10}$ cells per gram), including many thousand species of bacteria, fungi, algae, protozoa and viruses, most of which have yet to be identified and less than 10% of which can be currently classified. These microbes carry out vital life-sustaining functions, including cycling of nutrients such as carbon, nitrogen and phosphorus, and promoting plant growth; many microbial pathogens are also present. Soil microbes live in highly diverse communities that interact with each other, plants and the environment in complex ways. Because most of the microbes cannot be cultured, we still have little understanding of these interactions.

### Core challenges

Exploit the recent advances in genomics and advanced biochemical techniques, which provide the necessary diagnostic tools, to understand the links between microbial community composition, activity and soil ecosystem processes.

### Key research priorities

- To determine the effect of external factors on soil microbial communities and their functions, such as decomposition and nutrient cycling. External factors should include:
    - Physical factors, such as agricultural practices, for example tillage, crop rotation and fertilization, including the use of non-chemical forms such as manure or green waste composts. These factors have been demonstrated to have effects on soil biota and associated functions. Mycorrhizal fungi are known to have a reduced or altered diversity under conventional agriculture compared to reduced tillage, organic or more natural systems and little information is available relating to the function of different species under different agricultural systems. Nitrogen cycling microbial groups are known to be affected by similar changes in practice, but in contrasting directions where increased flux through the nitrogen cycle driven by fertilization results in high levels of greenhouse gas emission from agricultural systems. Our understanding of these and other soil groups is hampered by the difficulty of working in soil, mainly due to system complexity, including the highly multifunctional nature of most soil species and low culturability.
    - Chemical factors, such as use of fertilizers and how this relates to run off.
    - Environmental factors, such as drought and increased temperature due to climate change.
- To understand the impact of the plant and the plant genotype on soil microbial communities, in particular the effect of plant exudates on the communities. The plant provides an opportunity to manipulate the soil system in perhaps its most active habitat, the rhizosphere. Recent evidence demonstrates differences in the microbial community structure of the rhizosphere both within and between plant species. It is a high priority to gain an understanding of the functional consequences of these differences. Of particular interest is the role that plant breeding has had in shifting communities of microbes colonizing the root.
- To understand the role that microbes play in nutrient cycling, for example the role of soil microbes in nitrate leaching, which is a major environmental problem, and in the recovery of phosphorous from sewage and waste water.
- Better use of modelling systems using different soil types and soil qualities to predict the impact of external factors on soil microbial communities.
- Research needs to make use of new tools, such as genomics and metagenomics linking to functional tools, to assess the linkage between community characters and activity. Additionally, there is an increased requirement to develop and apply simple methods to assess soil quality.

## 2. Plant–microbe dynamics

Many complex crop–microbe interactions occur at all stages of crop growth from seed to product; they can be beneficial, harmful or neutral. Relationships that range from mutualistic, where both plant and microbe benefit, to parasitic, where the microbe receives some benefit from the interaction at the expense of the host, can all be considered as part of the complex symbiotic ecology. Pathogenic interactions occur when host plant cells are actively killed by the microbe to facilitate exploitation (see *Theme 3 – Crop pathogens*, p. 20). Some micro-organisms transition through several different relationships with plants during their life-cycles, and manipulating them in any one relationship will benefit from understanding the transition state triggers. This has implications for pathogen control, where application of fungicides may best be implemented at non-pathogenic stages. An example of an interaction that is neutral for the plant, but disastrous for human health is the carriage of food-borne pathogens. There has been a recent increase in cases of food-borne illness associated with plant-associated transmission of food-borne pathogens, for example the recent *Escherichia coli* O104 outbreak in Germany that was associated with contaminated seeds and affected over 3,500 people, more than 1,000 of these seriously.

Many microbes, in particular mycorrhizal fungi, rhizobia and viral, bacterial and fungal endophytes, confer direct benefits on their host plants in return for resources, such as carbon. These relationships are little exploited, especially in our major crops. Similarly, the role of host plant diversity in maintaining microbial stability in crop systems and the cost of microbes to crop productivity need to be determined. However, agronomic approaches may need to be changed to optimize these associations.

### Core challenges

To understand the nature and control of signals that trigger and change plant–microbe interactions and to develop strategies to exploit these trigger signals to favour more symbiotic, mutualistic states in microbial life-cycles. A need also exists to enhance the efficacy of mycorrhizal, rhizobial and endophytic associations with plants in stable, diverse communities. These challenges need to be investigated in several microbe–crop associations required for food security.

### Key research priorities

- Understand what triggers make microbes enter the different stages of their life-cycles in relation to their hosts and to determine whether these control mechanisms are environmentally driven (for example by temperature) or come from plant signals.
- Develop a greater understanding of beneficial plant–microbe interactions and how these can be enhanced and/or exploited by shifting microbial community structures towards stable, benign states (rather than eliminating detrimental microbes), and to understand the food safety implications of the dynamics of the association of animal, including human pathogens with plants.
- Enhance the function and host range of mycorrhizal fungi and rhizobia, which associate with roots, and provide plants with mineral nutrients and fixed nitrogen, respectively, in exchange for carbon.
- Identify and exploit endophytes (bacteria viruses or fungi that live within plants) that confer tolerance to stresses.

- Deploy diversity, particularly traits that reduce epidemic severity, at all scales from within crops to geographical regions to keep microbial populations stable and benign, and reduce opportunities for new pathogens.
- Reduce the transmission of human food-borne pathogens on plant materials (also reduce the carriage of spoilage microbes).
- Determine the cost of different plant–microbe relationships to non-target effects such as yield in crops and how this might be manipulated in crop health through novel treatments, including resistance priming with elicitors (analogous to immunization).

## 3. Crop pathogens

Crop production continues to be lost to pests and diseases; for four major world crops, actual losses are estimated at £150bn, with potential losses (without crop protection) at £275bn [12]. Disease control measures (for example crop resistance to pathogens, fungicides, rotation) reduce crop losses and help to alleviate food shortages, but their implementation needs to be optimized. Changes in climate and pathogen populations may increase the severity of crop disease epidemics and further threaten food security, especially for those farming in marginal environments.

### Core challenges

To understand the causes of crop diseases and their impacts on food security, including the role and production of mycotoxins, and develop strategies to intervene in situations where crop losses may occur. To guide government and industry strategies by using models to predict the effects of changes such as climate change, movement of pathogens and changing agricultural practices on crop–disease interactions. To identify and exploit sources of durable resistance, particularly utilizing crop and pathogen genomic data.

### Key research priorities

- Develop strategies to limit movement of invasive plant pathogens by identifying and monitoring routes of entry into new areas and implementing legislative controls, including destruction of infected plants and plant products.
- Exploit crop and pathogen genomic data to identify essential, invariant pathogenicity effectors likely to lead to identification of receptors and thereby durable crop resistance.
- Identify durable crop resistance against pathogens that is robustly expressed when exposed to various stress factors (abiotic or biotic).
- Exploit new methods for monitoring pathogen populations (for example combining air sampling with molecular diagnostics) to detect changes in pathogen populations (for example species movement, change in pathogen range, fungicide resistance, new races) so that control strategies for existing and emerging pathogens can be developed.

- Develop more accurate predictions of impacts of changes in climate, environmental and agricultural practices on losses from specific crop diseases, to identify those diseases that will increase/decrease in importance to guide government/industry strategies for adaptation.
- Understand the role of crop disease control in climate change mitigation (decreasing greenhouse gases). It is estimated that use of fungicides on UK arable crops currently saves 1.6 Mt $CO_2$ equiv. per season.

## 4. Gut microbiology in farm animals

The complex and diverse microbial population in the gut of farm animals, consisting of archaea, bacteria, protozoa and fungi, plays a central role in increasing the production of high-value human food from farmed livestock. At a global scale, livestock farming contributes up to 18% of total greenhouse gas emissions [18]. In Europe, livestock-related methane emissions result from the fermentation in the digestive tract of ruminant animals (70%) and in animal waste (30%). Thus in order to improve the greenhouse gas balance of farming, there is a requirement to reduce methane production by ruminants and to improve digestive efficiency to reduce excreta. It is also becoming obvious that microbial transformations in the gut can lead to the production of breakdown products (for example conjugated linoleic acids form during fatty acid biohydrogenation in the rumen) that are beneficial to human health. Ruminant production systems will increasingly focus on better use of lignocellulosic biomass either from waste material or forages grown on land not suitable for direct cropping, and must be optimized to reduce the production of greenhouse gases and to produce products which promote human health. The microbiota of all livestock is important in the retention of energy from the diet as well as the development of the immune system. Understanding the microbial communities and activities underlying these processes is therefore essential to ensure the efficient use of raw materials and maturation of host defences. In monogastric farm animals, microbiological studies have and will continue to lead to increased digestive efficiency and reduced pathogen transfer into the food chain.

### Core challenges

To improve our understanding of the interactions between farm animals and the microbes that live within them in order to increase productivity and promote human health while reducing the environmental and welfare impacts associated with livestock agriculture.

### Key research priorities

- To develop novel methods to modify the gut microbial community to decrease the production of greenhouse gases from farmed livestock.
- To analyse metagenomic and metabolomic data to understand the constituents and activities of the microbiota of livestock in totality and *in situ* to improve digestive efficiency.
- To improve the efficiency of forage (current and novel forages produced in response to climate

change) and by-product usage in farmed livestock to decrease the competition between farmed livestock and humans for feedstuffs.

- To understand how microbial transformations occurring in the gut influence the health-giving properties of food derived from animal sources.
- To understand how the indigenous microbiota protects against invading microbes, for example by defining the microbes and constituents thereof that mediate competitive exclusion and the maturation of mucosal immunity.
- To understand how the genetic make-up of the animal interacts with the microbial population in the gut and how this might be matched to available feedstuffs to maximize productivity and minimize environmental impact.

## 5. Animal pathogens

Infectious diseases are a major threat to the productivity and welfare of food-producing animals and to pollinating insects. Such diseases constrain trade, the prosperity of rural and developing communities and our ability to feed a global population that is growing in size and affluence. Improvements in animal health and productivity will ease demands on raw materials, including crops and agricultural land on which humans also rely. The intensification of animal production, together with an expected narrowing of genetic diversity of food-producing animals, is likely to lead to an increase in the burden of animal diseases and may see the emergence of new pathogens. The situation is exacerbated by the spread of resistance to antimicrobial agents among animal pathogens (which also blunts weapons used to treat human infections) as well as a decline in the rate of discovery of novel drugs and a decline in the facilities and expertise required to address challenges to animal health. Around 70% of human infectious diseases that have emerged in the last six decades have their origins in animals [14], and the vast scale of animal production suggests that new zoonoses will arise in the future. In addition to economically important endemic animal diseases, such as bovine tuberculosis, mastitis and respiratory and enteric diseases, the UK is threatened continually by 'exotic' pathogens, including emerging vector-borne diseases as a consequence of environmental change. Introduction of such exotic pathogens can profoundly affect trade, as evidenced by the impact of UK epidemics of foot-and-mouth disease, and erode public confidence in food, as with mad cow disease. Control of infectious diseases of animals is most effective when vaccination is used together with state-of-the-art diagnosis and surveillance. Advances in gene sequencing, the immunology of food-producing animals and the ability to manipulate microbial genomes will provide new opportunities for diagnosis and control of animal pathogens.

### Core challenges

To develop, improve and implement methods for the rapid diagnosis and control of the approximately 80 infectious diseases of food-producing animals and fish and pollinating insects recognized by the World Health Organization for Animal Health as being of global or regional significance [23].

### Key research priorities

- For many important infectious diseases of food-producing animals, fish and pollinating insects, improved methods for rapid and specific diagnosis, including simple on-farm tests, are needed to speed up detection and provide a network of global intelligence on the spread of infectious diseases.
- To aid analysis of risk, targeting of resources and control measures, and the development of effective control strategies, an understanding is needed of the molecular basis of host–pathogen interactions with emphasis on identification of:
    - mechanisms of pathogen colonization and persistence;
    - mechanisms of host or tissue tropism of pathogens;
    - virulence determinants and the basis of pathology;
    - mechanisms of innate and adaptive immunity to pathogens;
    - factors influencing transmission between hosts, including the role of wildlife;
    - factors influencing pathogen evolution and the emergence of new pathogens;
    - components of pathogens that can be targeted by drugs, or which are suitable for inclusion into vaccines;
    - the effect of co-infections with different micro-organisms (including indigenous microbes) on the outcome of infection.
- To determine the effects of climate/environmental change on the dynamics of disease transmission and geographical spread.
- The development of new disease control strategies, including pre- and probiotics, immuno-stimulants and medicinal plant or microbial products. Research into probiotics for aquatic organisms is increasing with the demand for environment-friendly aquaculture.
- Development of disease-resistant animals by selective breeding or transgenesis based on knowledge of pathogen biology.

## 6. Food spoilage

Food spoilage may be defined as any change that renders food unfit or unsafe for human consumption. Microbiological spoilage is a significant problem with respect to the shelf life of raw and processed foods (meat, fish and vegetable products) and is a key contributor to food waste. Future food security will necessitate that less food is wasted. More than 25% of the food that is bought is wasted because of delays in the food chain, poor storage and human behaviour [16]. Contamination and spoilage may occur at any stage along the food chain from harvest to retail, where bacteria, yeasts and moulds cause microbial spoilage. An area of concern is the safety of ready-to-eat meals that use diverse sources of ingredients in support of an expanding value-added market within the UK.

### Core challenges

A central issue is the adaptation of communities of microbes to specific environments, both pre- and post-harvest. The globalization of food production with, for example, legislation and guidelines that apply in the UK not necessarily applying elsewhere, could give rise to new hazards, and the centralization of post-harvest storage and processing mean that any problem can effect a wide number of consumers across national borders. Until it is understood how these organisms survive and adapt to conditions at harvest, during storage and processing, then microbial spoilage will remain a barrier to the efficient use of food and potential source of infection. Adaptation is also an important consideration in terms of the detection of pathogens that can reside within mixed communities below detection limits, or in a 'non-detectable' state. There is a need to consolidate and standardize methods for understanding microbial contamination or growth on pre- and post-harvest foods.

### Key research priorities

- Understanding microbial ecology of pre- and post-harvest produce, and how these microbial populations can affect shelf life and food quality.
- To be able to track microbial spoilage and pathogen sources in order to predict pre- and post-harvest hazards to inform farmers and food processors on storage and process control measures.
- The development of rapid diagnostics to allow for correct species and strain identification from within mixed microbial communities and develop databases for the food source attribution of microbes.
- Develop an understanding of how to optimize the food chain, improve shelf life and produce intelligent packaging.

## 7. Food safety and human diseases

Food-borne illnesses are a serious global problem and a need exists to improve food safety while improving consumer choice and the welfare and productivity of animals. The World Health Organization estimates that worldwide food-borne and water-borne diarrhoeal diseases taken together kill about 2.2 million people annually [24]. In the UK, it is estimated that about 1 million people suffer a food-borne illness of which 20,000 receive hospital treatment, and there are over 500 deaths. This cost to the UK economy in 2009 was about £2bn [15]. Such infections can have life-threatening consequences and vaccines or treatments for most food-borne pathogens are lacking or ineffective. The evolution of food-borne microbes has been punctuated by the emergence of new problems, for example *Salmonella enterica* serovar Enteritidis phage type 4, responsible for an on-going pandemic associated with egg contamination, and Shiga toxin-producing *E. coli*, which first manifested as *E. coli* O157 in the early 1980s and more recently in an unusual 'hybrid' O104 strain that infected over 3,500 people in Germany in 2011, killing 50 and producing life-threatening conditions in over a quarter of patients. Other threats have grown over time: cases of *Campylobacter* (mainly poultry-associated) now account for the majority of food-borne illness, with around 724,000 infections [25] estimated to have occurred in the UK during 2010 and around 65% of chickens on retail sale being contaminated [26]. *Listeria monocytogenes* infections (usually associated with ready-to-eat produce) also raise concern due to the high level of mortality. Infection can be fatal in one-third of cases in susceptible individuals [10]. The proportion of all food-borne outbreaks due to fresh fruit and vegetables contaminated with animal excreta, for example by using untreated manure, has increased significantly in recent years. Large-scale outbreaks can produce political and trade implications over and above the public health cost.

### Core challenges

To enhance the microbiological safety of food it is necessary to minimize contamination of food supply chains by pathogens and to eradicate or control any pathogens that are present. It is necessary to identify all routes by which pathogens contaminate each food supply chain and to define the activities of microbes throughout in order to target new and effective control strategies to reduce microbial persistence and transmission. Moreover, improved tools are needed to identify emerging pathogens and assess the zoonotic and epidemic potential of microbes found in food-producing animals and the environment.

### Key research priorities:

- To understand pathogen biology throughout the food chain in order to develop and refine strategies that reduce transmission/persistence of pathogens in the food chain, and in turn human disease.
- Define the nature, frequency and consequences of genetic exchange and variation in food-borne microbes to aid assessment of risk and targeting of control strategies.
- To understand the role of husbandry practices, diet and health of food-producing animals in the carriage of zoonotic pathogens.
- Define the transmission pathways of food-borne pathogens with emphasis on the points of entry of pathogens into food supply chains and the persistence and activities of microbes in varied production niches.
- Development of effective food-processing approaches based on improved understanding of pathogen biology and quantitative microbiology to improve food safety and to extend shelf life and quality of food.
- Development of improved methods to detect food-borne microbes and assess the risk they pose, including rapid detection of viable or infectious agents, for example in non-culturable states.

## 8. Waste reduction and management

Waste occurs at all points along the food chain. This includes those parts, such as straw or animal slurry, ancillary to the food itself, losses due to spoilage in the field and during processing, losses due to perceived low quality and domestic food waste. While other themes are concerned with reduction of waste, this theme deals with what to do with waste created.

At least half of food grown is discarded before and after it reaches consumers. It is estimated that in the UK one-third to half of landfill waste comes from the food sector. Landfill releases greenhouse gases, in particular methane, which contribute to climate change. The Waste Hierarchy (in order of preference: Prevention, Re-use, Recycle, Other recovery, Disposal) states the common sense and now legal approach to waste disposal, the specific method being dependent on the nature of the waste. In the context of food security and safety, waste can be converted into products for further use (for example animal feed, compost) or sources of energy (for example biogas in anaerobic digestion, bioethanol in refineries, or burned directly in power plants). The production of ethanol, butanol and other foods from food waste helps reverse the trend of using agricultural resources to produce biofuel rather than food. However, it is important to remove pathogens from waste in order to prevent them re-entering the food chain, and where possible reduce spoilage microbes.

Microbiology is central to most of these processes. The modification and exploitation of food wastes using microbiological routes may be considered as part of a biorefinery process in which high-value components may be initially extracted from the waste prior to exploiting the residue.

### Core challenges

The core microbiological challenges of waste management concern optimization and matching of microbial processes to specific waste streams. This is another example of where we need much better understanding of the ecology of microbial communities.

### Key research priorities

- Improved production of cell-wall-degrading enzymes from microbial sources for the commercial disassembly of plant structures. At the moment, enzymes used in cell wall saccharification are still overly expensive.
- Microbial optimization of waste treatment. The sequence of microbiological processes underlying anaerobic digestion requires further investigation to improve the production of methane and reduce the problems caused by heterogeneous wastes, and to ensure safety.
- Removal of pathogens (and reduction of spoilage microbes) from plant and animal waste to prevent them re-entering the food chain.
- Generation of useful products from food waste through the use of targeted microbial degradation.
- Reduction in methane release through better control of microbiology in landfills.

## 9. Novel methods

The development and application of novel methods can revolutionize the approaches taken by industry and academia to study and address issues affecting food safety and security. These new methods are very diverse and include practical methods to rapidly detect, study and manipulate microbial genomes; the development and use of microbes as biocontrol agents to control crop pests; modelling-based systems that can improve the understanding of the effects of changes in food production and processing and how these affect microbiological risks in the food chain; methods of remote sensing that can be used in surveillance, tracking and monitoring on both local, national or global levels; development in information collection and analysis systems that allow the recording and assessment of large amounts of complex multi-dimensional data to allow logical and valid conclusions to be drawn.

### Core challenges

The core challenges are to understand what novel methods are becoming available and how these could be employed within the food chain to help in the understanding and improvement of food safety and security issues. Key are the developments in 'omics technologies that allow a detailed study of the microbial genome, an insight into microbial diversity within foods and the potential to develop rapid detection methods for new pathogens. This requires an ability to handle and analyse large amounts of information with suitable bioinformatics approaches. Continuing with information handling and analysis approaches, the development of modelling systems that will enable prediction of the effects of changes to food production procedures would allow for better risk assessment and identification of potential new hazards.

### Key research priorities

- Development, use and application of 'omics technologies to study and understand microbial diversity and interactions within the food chain. This will include 'active' organisms, stressed 'non-culturable' organisms, and organisms containing or with the ability to produce compounds that will affect food safety and security. This includes an ability to assign roles to particular genes. This will allow the identification of the complete microflora contained within foods and allow us to understand their interactions, which will have effects on safety (through competition of pathogens with other innocuous microflora) and shelf life (more accurate identification of spoilage flora will allow development of effective strategies for their elimination). Additionally, such methods could allow metabolic modelling of nutrient cycling and metabolism in complex microbial communities in soil and the plant rhizosphere.
- Development of technologies that would allow rapid implementation of simple (potentially point of use) tests for a range of organisms that may be new/novel animal or plant pathogens. Tests allow for rapid identification, helping with control of these organisms and increasing safety within the food chain.
- Development of suitable data handling, management and analysis systems (hardware and software) to help us to data-mine, analyse and understand results from the large amounts of data produced by current and future novel methods. This will allow the fast analysis of complex datasets, yielding results such as identification of microbial communities and identification of particular genes within organisms that could encode either beneficial or negative microbial effects.

- Study and use of microbial biocontrol agents for crop pests (for example use of fungi or Bt toxin to control insects). This would allow an effective control of pests without the use of chemical pesticides, thus reducing the use of chemical pesticides in agriculture.
- Development of modelling and risk-based approaches that could be used to predict the effects of changes in food production methods, or indeed how extraneous events could affect food safety and security, for example climate change effects across large geographical areas.

# Genetically modified organisms (GMOs)

While earlier sections of the document have been silent on the subject of GMOs, the laboratory use of genetic modification is an important tool in microbiological research. Furthermore, the generation of genetically modified products under appropriate safety protocols is increasing in many parts of the world and could be beneficial to the UK. The following are examples.

- Genetically modified microbes can be used as vaccines to protect against infectious diseases of animals, including man. Pathogens that have been weakened by alteration of their genetic material, or microbes that do not cause disease, can be engineered to produce foreign antigens to stimulate host defences without causing harm. Many such vaccines have now been licensed or approved, and more are being developed. For example, a recombinant vaccinia virus has been used in Europe to vaccinate foxes against rabies, and a herpesvirus of turkey (HVT), used as a vaccine to protect chickens against Marek's disease, has been engineered to produce antigens from Newcastle disease (ND) virus and infectious laryngotracheitis (ILT) virus and is being used to protect poultry against all three agents in a single dose. This technology can now be applied to develop genetically modified microbes that induce greater protection, longer-lasting immunity, or which are more stable or cross-reactive.
- Genetically modified microbes can be harnessed as sources of useful molecules, including enzymes to aid energy retention from animal diets and insecticidal toxins to control crop pests and vectors of animal disease. Knowledge of pathogen biology can also be used to engineer animals or crops that resist disease. For example, transgenic chickens were recently described that fail to transmit avian influenza owing to expression of decoy RNAs that sequester viral proteins [27], and a similar strategy can be used in crops to instill resistance to plant viruses [28].

The SGM sees significant potential in the use of biotechnology research to mitigate food insecurity and the use of GMOs as just one of the many tools in the researcher's toolbox that, with rigorous legislative and ethical review, may yield products or processes to improve food security. SGM will continue to inform the debate about the use of such technology.

*Escherichia coli* bacteria. *Eye of Science/SPL*

# Resources needed to support research programmes

For world-class research to continue in the UK on food security and safety the SGM has identified the following facilities which will need to be developed and/or maintained:

- Containment facilities for pathogens of plants, animals and humans, including Home Office licensed animal and aquaria facilities.
- Farm-/field-scale facilities.
- Controlled environments (climate change).
- Culture collections, and the systematists and specialist technicians required to actively curate them.
- Animal and plant models of disease.
- High-speed data communications for real-time information.
- Supercomputing resources for data-mining and bioinformatics.

There is a shortage in undergraduate and postgraduates with research skills in traditional microbiology – i.e. non-reductionist/molecular and expertise gaps in subjects such as mycology, plant virology, food microbiology, soil science and insect pathogens, and those working with microbes in target animals and crops. There will be an increasing requirement for quantitative scientists with appropriate skills in both microbiology and maths to carry out microbial risk analysis, model and predict likely outcomes and make best use of data available.

There will also be a need for graduates with high-level skills that can apply new technologies and developments arising from this, for example in microbial bioinformatics.

It is important that the present (and any future) economic downturn does not result in a reduction in the microbiology skill base (in its broadest sense) or the provision of containment facilities and other necessary facilities.

Nitrogen-fixing root nodules on pea roots. *Wally Eberhart, Visuals Unlimited/SPL*

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## Food Security and Safety Expert Panel

**Professor David White CBE (Chair)**

Former director of the Institute of Food Research

**Professor Nigel Brown (SGM Council)**

University of Edinburgh

**Professor Martin Adams**

University of Surrey

**Professor Brian Austin**

Institute of Aquaculture, University of Stirling

**Dr Roy Betts**

Campden BRI

**Professor Ian Connerton**

University of Nottingham

**Dr Nigel Cook**

Food and Environment Research Agency

**Professor Bruce Fitt**

University of Hertfordshire

**Dr Nicola Holden**

The James Hutton Institute

**Professor Tom Humphrey**

University of Liverpool

**Professor Naresh Magan**

Cranfield University

**Professor Jamie Newbold**

Aberystwyth University

**Dr Adrian C. Newton**

The James Hutton Institute

**Professor Michael Peck**

Institute of Food Research

**Dr Phil Poole**

John Innes Centre

**Professor Robert Possee**

Centre for Ecology & Hydrology

**Professor Olivier Sparagano**

Northumbria University

**Dr Adam Staines**

Agri-Food, BBSRC

**Professor Mark Stevens**

The Roslin Institute & Royal (Dick) School of Veterinary Studies, University of Edinburgh

**Dr Geraldine Taylor**

Institute for Animal Health

**Dr Richard Thwaites**

Food and Environment Research Agency

**Professor Marion Wooldridge**

Animal Health and Veterinary, Laboratories Agency

## SGM Food Security and Safety Project Team

| | |
|---|---|
| **Dariel Burdass** | Head of Education and Public Affairs |
| **Laura Udakis** | Press and Social Media Officer |
| **Shweta Shetty** | Intern |
| **Yvonne Taylor** | Public Affairs Administrator |
| **Ian Atherton** | Proof-reader and Design Manager |

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# Partners

### Society for General Microbiology (SGM) – www.sgm.ac.uk

The SGM is a professional body for scientists who work in all areas of microbiology. It is the largest microbiology society in Europe, and has over 5,000 members worldwide. The Society provides a common meeting ground for scientists working in research and in fields with applications in microbiology including medicine, veterinary medicine, pharmaceuticals, industry, agriculture, food, the environment and education. An important function of the Society is promoting the understanding of microbiology to key stakeholders, including policy-makers, Members of Parliament and the House of Lords. SGM publishes four world-renowned, peer-reviewed journals: *Microbiology*, *Journal of General Virology*, *International Journal of Systematic and Evolutionary Microbiology* and *Journal of Medical Microbiology*.

### Society for Applied Microbiology (S*f*AM) – www.sfam.org.uk

S*f*AM is the oldest UK microbiological society and the voice of applied microbiology within the UK. S*f*AM has members across the globe from all sectors of applied microbiology.

S*f*AM works in partnership with sister organizations and microbiological bodies to ensure that microbiology and microbiologists are able to exert influence on policy-makers within the UK, in Europe and worldwide. S*f*AM publishes five internationally acclaimed journals with Wiley-Blackwell: *Journal of Applied Microbiology*, *Letters in Applied Microbiology*, *Environmental Microbiology*, *Environmental Microbiology Reports* and *Microbial Biotechnology*.

## British Mycological Society (BMS) – www.britmycolsoc.org.uk

BMS is a registered charity open to all who are interested in promoting and learning about the exciting world of fungi. It has member sections devoted to particular aspects of the fungal world, including cutting-edge research into many aspects of fungal science, the conservation and recording of fungi and the provision of educational resources for use at all ages and experience. If you are working with, fascinated by or wish to learn about fungi the Society can help. The BMS has 800+ members worldwide and also publishes a number of peer-reviewed scientific publications, including *Fungal Biology*, *Fungal Ecology*, *Fungal Biology Reviews* and *Field Mycology*.

Control of fungal pathogens, the development of new diseases of staple crops, minimization of fungal spoilage and decomposition processes will all require the expertise of fungal biologists to help in addressing climate change and food security issues. For more information on the BMS, please check our website or contact the President of the BMS, Professor N. Magan (n.magan@cranfield.ac.uk).

## British Society for Plant Pathology (BSPP) – www.bspp.org.uk

BSPP supports the professional interests of plant pathologists worldwide. We publish articles in the high-quality journals *Molecular Plant Pathology* and *Plant Pathology* (no page charges, except colour). Members can apply for travel awards, short-term visiting fellowships, summer student funds, conference support and to promote of plant pathology to the public.

society for general Microbiology
www.sgm.ac.uk

# Position Statement on Food Security and Safety

## Executive summary

# Executive summary – key conclusions for policy-makers

Microbiological research has been and continues to be central to meeting the global challenges of food security and food safety, defined by the Food and Agriculture Organization [1] as '*when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life*'.

With the world's population predicted to rise from its current 7 billion to 9 billion by 2050, producing enough food to feed this expanding population has been recognized as one of the greatest challenges facing mankind. In 2011, a major 2-year study from the UK Government Office for Science 'Foresight' programme *The Future of Food and Farming* [2] was published, outlining the emerging issues and challenges to global food security and safety. A number of action plans to meet this challenge have been published by the relevant global agencies, including UK government departments, research councils, the Royal Society and others [3, 4, 5, 6, 7].

The Society for General Microbiology (SGM) in partnership with other leading microbiology and microbiology-related organizations, the Society for Applied Microbiology, the British Mycological Society and the British Society for Plant Pathology, is concerned that the role of microbiology in meeting these challenges is poorly understood and under-represented at a time when funding for universities and institutes has been cut, leading to a shortage of expertise in many important microbiology disciplines across the UK [6].

Food security is not just about increasing food productivity; it is also about wasting less. Furthermore, supplying safe, nutritious foods must be achieved in a sustainable manner with minimal impact on the environment and animal welfare. Meeting the challenges is exacerbated by a number of key drivers and constraints, including climate change, energy usage, mineral and water availability and population dynamics, and to be sustainable must occur within the '*safe operating space for humanity*' identified by Rockström *et al.* [8].

Microbes (bacteria, fungi, viruses, protozoa, algae and archaea) and their activities are involved at every step of the food chain. Understanding the role of microbes at all steps in the process of plant and animal production, soil and water management, and harvesting, storage and processing of agricultural products is necessary. Now and in the future, microbiological research and development will play a profoundly important role in sustaining and improving food production, food safety, and environmental quality while reducing waste.

Critically, investment in microbiological research and development to tackle food security and safety will have measurable socio-economic benefits. For example, for every 1% reduction in crop pests and diseases it has been estimated that an extra 25 million people could be fed [9], and for each 1% reduction in the overall incidence of UK food-borne disease it has been estimated that there would be around 10,000 fewer cases each year; this 1% represents an economic saving of around £20 million [15].

History records that microbiological research has delivered major advances in food security and safety. Important milestones include:

- Identification and application of safe processes for food preservation, such as canning and pasteurization, and understanding the biology of pathogenic and spoilage microbes to reduce their transmission in the food chain, leading to developments of safer foods with a longer shelf life.
- Exploiting antimicrobial substances produced by naturally occurring microbes as weapons against plant and animal pathogens.
- Vaccine development to improve the health of livestock and reduce transmission of animal pathogens to humans.
- Producing novel food products, including probiotics and nutritionally enhanced food through fermentation.
- Exploiting microbial processes to manage or reduce waste.

It needs to be recognized that there are key overarching factors which impact on microbiological activity, including:

- Microbes do not respect international boundaries and consequently food-borne pathogens, and also animal and plant diseases, such as foot-and-mouth disease, classical swine fever, coffee leaf rust and soybean rust, can be spread rapidly worldwide via trade, travel or arthropod vectors, depending on the pathogen, to new geographical areas. Moreover some microbes move between animals and humans, introducing diseases and resistances to antibiotics.
- In their natural habitat, microbes live in diverse, complex, interdependent communities, the ecology of which must be fully understood if we are to eradicate disease and exploit the beneficial role that microbes play in achieving food security.
- Many microbes have the capacity to evolve rapidly to become better suited to *their* environment, not necessarily to our benefit, thereby changing their behaviour and meaning that continual vigilance is required. Such evolution can allow microbes to escape control by drugs or vaccines, meaning that diseases that were once considered under control may re-emerge.

Nine research themes have been identified where the role of microbiological research is crucial to help meet the challenges of ensuing global food security and safety.

## Research themes

Within this Executive Summary, just two areas of necessary research are identified for each theme. The full report provides a more detailed set.

### 1. Soil health and nutrient cycling

The soil microbial community is largely uncharacterized, but is responsible for decomposition of organic material and biogeochemical cycling to provide plant nutrients, capture and release of essential minerals, and maintenance of soil structure. Microbial respiration of nitrate is estimated to account for as much as one-third of the loss of fertilizer or other nitrogen sources from soil-containing plants [11]. Further research into the soil community and role in nutrient cycling will allow optimization of nutrient yield, for example research to:

- Understand the role of microbes in nutrient cycling, particularly phosphate, nitrogen and micronutrient metals.
- Determine the effect of external factors on soil microbial communities and their functions, such as decomposition and nutrient cycling.

### 2. Plant–microbe dynamics

Microbial interactions with plants can be beneficial (for example nitrogen fixation or mineral uptake in root systems), parasitic or pathogenic. Microbes can switch between beneficial, parasitic and pathogenic stages during their life-cycles; understanding these change triggers is essential for controlling pathogens and enhancing beneficial interactions to maximize crop yields in a sustainable way. Research is needed to:

- Enhance beneficial (for example mycorrhizal, rhizobial or endophyte) plant–microbe rhizosphere (volume of soil around the plant roots) and phyllosphere (leaf surface habitat for microbes) interactions to enhance nutrient uptake and stress tolerance.
- Understand and exploit the triggers that change microbes between beneficial, parasitic and pathogenic stages of their life-cycles as a means to identify durable crop resistance and better target crop protection.

### 3. Crop pathogens

Pests and diseases can considerably decrease crop production with current losses, estimated to be more than £150bn worldwide [12], contributing to global food insecurity. There are opportunities to exploit new methods and models to decrease disease-induced crop losses. Research is needed to:

- Identify crop resistance against pathogens that is durable through exploitation of new crop and pathogen genomic data, and new understanding of factors affecting severity of epidemics.
- Guide government/industry strategies by exploiting new models to predict impacts of changes in climate and agricultural practices on severity of crop diseases.

## 4. Gut microbiology in farm animals

The complex population of micro-organisms in the gut of farm animals plays an important role in the nutrition and health of the animal. In sheep and cattle, microbes are responsible for conversion of plant material into energy and protein to support meat and milk production, but also production of methane, a potent greenhouse gas. In pigs and poultry the gut microbes play a key role in digestive efficiency and in preventing the passage of pathogens. Research is needed to:

- Develop novel methods to modify the gut microbial population in beneficial ways, for example to improve energy retention from the diet and to decrease the production of greenhouse gases from farmed livestock.
- Understand how indigenous microflora in the gut protects against invading microbes.

## 5. Animal pathogens

Infectious diseases of food-producing animals result in reduced efficiency or significant losses in food production from animals and adversely affect animal welfare and trade. With nearly 700 million of the world's poorest people relying on farming animals for their survival [13], effective control of animal pathogens is crucial not only for safeguarding and securing national and international food supplies, but also for alleviating rural poverty in developing countries. Research is needed to:

- Develop novel and improved rapid diagnostic tests, including simple on-farm tests, in order to detect outbreaks early enough to effect containment (c.f. 2001 UK foot-and-mouth disease outbreak).
- Develop effective control measures, such as new antimicrobial compounds and novel or improved vaccines that induce long-lived immunity and/or which protect against multiple strains of the same pathogen.

## 6. Food spoilage

Food spoilage may be defined as any change that renders food unfit or unsafe for human consumption. Microbiological spoilage is a significant problem with respect to the shelf life of raw and processed foods (meat, fish and vegetable products) and is a key contributor to food waste. Future food security will necessitate that less food is wasted. Research into optimal storage and transport conditions, methods of food preservation and reduction in microbial contaminants will contribute significantly to the amount of food available, particularly in the developing world. Research is needed to:

- Understand the microbial ecology of pre- and post-harvest produce, and how these microbial populations can affect shelf life and food quality.
- Develop rapid diagnostics to allow for correct species and strain identification from within mixed microbial communities and understand the food source attribution of microbes.

## 7. Food safety and human diseases

Sustainable production of safe and nutritious food requires improvements in food safety. Of 335 emerging infectious diseases over the last 70 years, 60% have been acquired through animals (note that 60% relates to all zoonoses and not just food-borne ones) [14]; intensive agriculture increases opportunities for evolution and spread of harmful microbes. Food-borne illness is a global burden. In the UK, it is estimated that about 1 million people suffer a food-borne illness of which 20,000 receive hospital treatment, and there are over 500 deaths. This cost to the UK economy in 2009 was about £2bn [15]. Research is required to mitigate this:

- To better understand the microbes, their hosts, environmental factors and the interactions between them that result in transmission of pathogens in the food chain and subsequently to food-borne disease.
- To develop strategies that reduce transmission throughout the food chain, infection and disease using appropriate research models, and to predict the zoonotic and epidemic potential of microbes found in animals by exploiting state-of-the-art technologies.

## 8. Waste reduction and management

More than half of the food grown is discarded before or after it reaches consumers and over one-third of landfill waste in the UK comes from the food sector. Such landfill releases greenhouse gases, particularly methane. The core microbiological challenges of waste management concern optimization and matching of microbial processes to specific waste streams. In particular, research into controlled anaerobic digestion is required to understand this process and convert waste into usable energy and fertilizer. For example, research is needed to:

- Understand how the microbial community in anaerobic digesters can be optimized.
- Improve production of cell-wall-degrading enzymes from microbial sources for the commercial breakdown of plant structures.

## 9. Novel methods

The vast majority of micro-organisms – whether beneficial, harmful or neither – remain to be discovered. Even the presence or absence of organisms we know may be difficult to determine. Research needs to focus on new identification techniques and accurate data acquisition to unravel the complexity of microbial communities involved in the production and utilization of food and for increased tracing of microbes through the food chain. For example, research is needed to:

- Develop data management systems that are capable of collecting, storing, analysing and communicating data.
- Develop methods to study unculturable microbes, which are becoming increasingly implicated in disease and environmental functions such as nutrient cycling especially in soil, and to trace pathogenic and spoilage microbes through the food chain.

The SGM recognizes that any proposed solutions to the challenges of food security and safety will require multidisciplinary, multinational teams to effectively meet the global challenges of our future food supply. However, to deliver potential solutions to this global issue, funds need to be committed to:

- Support microbiology research programmes and to procure the necessary resources required to deliver the proposed research.
- Support the training and development of skilled microbiologists.
- Provide world-class research facilities, including those needed to study microbes in the animal, crop or environmental systems where they act rather than surrogate laboratory-based models.