A Vision and high-level Strategy for UK Animal and Plant Health Research To 2020 and Beyond

HM Government:
Department for Business, Innovation and Skills, Government Office for Science,
Department for Environment, Food and Rural Affairs, Food Standards Agency,
Department for International Development, Public Health England

Foreword

The UK is home to world leading animal and plant health research. Building on these strengths, we need to capitalise on new research knowledge, tools and technologies. This will provide benefits to UK society, the economy and the environment.

Working within the spirit of a new science partnership, this UK level Animal and Plant Health Strategy sets out a shared science vision and framework to deliver improved science capabilities. Cutting-edge technologies, including the proposal for a UK Animal and Plant Health Internet of Things, have the potential to transform the way we understand, detect and respond to risks to animal and plant health.

Led by Professor Jackie Hunter (Chief Executive, Biotechnology and Biological Sciences Research Council), this Strategy has been developed collaboratively with key funders of animal and plant health research from UK government, the Research Councils, the Devolved Administrations, industry and academia, and has been constructed with broad community engagement.

This represents the first s eps in progress towards the new UK Science Partnership for Animal and Plant Health - a new model for science coordination and collaboration designed to prioritise research investment and to align strategic agendas and research programmes. This lays the groundwork for key funders from the public and private sectors to work together for the benefit of the UK.

With leadership from the new UK Science Partnership for Animal and Plant Health, a continuing push for coordination and collaboration, and a powerful capacity to work across disciplines, the UK will be better placed to address the many challenges facing us over the next few years with accompanying benefits to society, UK growth and productivity, and the environment.

Mark Walport

Government Chief Scientific Adviser
Chair of the interim Animal and Plant Health Science Implementation Group

Executive Summary

There are compelling economic, social and environmental drivers for a more robust and concerted UK response to animal and plant health challenges of critical importance to protecting and enhancing the nation's prosperity and wellbeing. The UK needs to develop a more integrated, whole-system approach to animal and plant health science to underpin this response.

This document sets out a high level research strategy, including actions and deliverables, for key research funders working within a new UK Science Partnership for Animal and Plant Health, and with wider research stakeholders. This research strategy, which has been developed with a wide range of stakeholders, from government, academia, industry and the third sector, is designed to realise the following vision:

By 2020, the UK will have created and harnessed new research knowledge and technology that will transform our ability to:

- **systematically predict, detect and understand key current UK animal and plant health problems and emerging threats in real time;**

- **direct sophisticated and rapid responses to effectively and efficiently prevent and mitigate impacts on our agri-environment and wider ecosystems and landscapes.**

In parallel, it will have created the optimal innovation environment for developing and trialling new interventions, stimulating inward investment and the development of new products and services through small and medium-sized enterprises and large national and multinational companies.

New knowledge, tools and technologies are providing exciting opportunities to realise this ambitious vision and to realise sustained, long-term benefits. Ho ever, effective action requires better *whole system* coordination of national scientific aims, skills and resources across s akeholders and across disciplines. This will allow the UK to build on existing UK capacity and strengths, make more effective and efficient use of limi ed resources, and to stimulate increased contributions from public and private funders.

There are a number of converging opportunities for the UK to develop a 21st Century integrated, scalable infrastructure to catalyse the development of 'next generation' national research capability and to improve the translation and impact of world-class UK research. The UK needs to build on the emerging internet of things to establish a UK Animal and Plant Health Internet of Things (UK-APHIoT) that would embed, at its heart, a web of flexibly in erconnected sensors and data nodes, alongside data from wider sources and advanced approaches to data management and analysis. This will deliver a step change in research capability and the translation of research benefits to respond to major problems and threats in a sophisti ated way.

The UK is well placed to deliver a UK-APHIoT, but there are key challenges to be addressed in driving forward its development, including: the integration of fragmented existing components; the development of effective data management frameworks for collecting, synthesising, analysing and communicating evidence; and the need to engage and incentivise end users. Pilot scale development and testing of a UK-APHIoT concept will allow these challenges to be systematically addressed on the road to developing a scalable framework:

ACTION 1: The new UK Science Partnership for Animal and Plant Health will establish the framework and operating pilots for a UK Animal and Plant Health Internet of Things, which will:

- **enable fast, systematic detection, analysis, understanding and prediction of animal and plant health risks**

- **direct the timely application of the most effective interventions and facilitate their uptake, and**

- **protect and strengthen the UK's rural and land use economy and stimulate inward investment by industry.**

Working within this enabling framework, it is necessary to:

- coordinate and build on existing UK strengths in essential frontier research, and capitalise on the potential of 'next generation' systematic and trans- and interdisciplinary research approaches;
- to develop new tools and technologies and the scientific and social in rastructure to enable their effective use, and;
- develop integrative approaches to collect, assimilate and analyse evidence to monitor, model and manage the impacts of animal and plant health challenges.

Three key research themes and associated deliverables have been identified to address these areas

ACTION 2: The new UK Science Partnership for Animal and Plant Health will prioritise research investment and align strategic agendas and research programmes around three key themes and nine deliverables:

I. Improved understanding of current and emerging pathogen and pest threats and how they may be controlled – growing and maintaining world class interdisciplinary science capability:

- To develop more systematic understanding of i) pest and pathogen biology and diversity, including ecology, evolution and transmission dynamics, and ii) pathogen-host interactions, including host immune responses.
- To accelerate breeding for sustainable resilience and resistance.
- To reduce the impact of anti-microbial, anti-parasitic and pesticide resistance in pathogens and pests of animals and plants.

II. New technologies to detect and control pest and pathogens – enhancing the UK's ability to develop, validate and use them:

- To develop and apply new technologies for faster, more sensitive and more efficient de ection of pests and diseases.
- To improve and create new technology platforms to combat endemic and emergent pests and diseases.
- To develop new field tools to guide precision in erventions.

III. Integrative approaches to monitor, model and manage endemic problems and emerging threats – guiding precision intervention at local and landscape levels:

- To develop next generation, integrative surveillance capability for animal and plant health.
- To develop more systematic and flexible modelling approaches to in orm effective pest and disease management.
- To understand and foster the role of environmental and agri-systems resilience in promoting animal and plant health.

Working within this framework of the proposed UK Animal and Plant Health Internet of Things, this strategic approach will deliver the next generation of capability, knowledge and technologies required to predict, detect and understand problems, and protect and enhance animal and plant health.

The next step will be for the UK Science Partnership for Animal and Plant Health to develop a more detailed action plan, and to identify areas for improved collaboration and coordination across the Partnership. Scoping work will be initiated, as a priority, on potential regional pilot scale activities to further explore the opportunities and challenges presented by the proposed UK-APHIoT.

I. Context

In December 2014, the Government Office or Science and Defra jointly published the report: ***Animal and Plant Health in the UK: Building our science capability***[1]. This study identified the need or an integrated strategy across government departments, the Devolved Administrations, research institutions, public research investors and end users to enable the UK to be better equipped to respond to the threats to animal and plant health to the UK's economic productivity, society and environment. It set out four initial priority actions as the first s ep in progress towards a new UK Science Partnership for Animal and Plant Health.

This document delivers **priority action 1** – *a UK-level strategy for animal and plant health science that identifies key priorities and critical scientific questions, defines the role for government and others, and sets out an action plan with accountabilities for delivery*. The findings rom **priority action 2** – *Value for Money from Public Investment in Animal and Plant Health Scienc*e – have (i) informed this science strategy and (ii) will inform considerations on future spending decisions.

This document sets out a vision and high level research strategy to guide key UK public funders and policy makers, academia and industrial stakeholders in working together to maximise the impact of investments and resources to address animal and plant health challenges of critical importance to protect and enhance the nation's prosperity and wellbeing. It aims to develop the higher level vision identified in the report *Animal and Plant Health in the UK: building our science capability*: –

'The UK has the science capability to protect and enhance the contributions animal and plant health make to society.'

There are signifi ant benefits in identi ying common opportunities and challenges, and associated high level research themes and deliverables. Building on existing strengths, this will inform greater alignment of approaches and capabilities and, where appropriate, increase cross-pollination of research expertise and ideas between sectors. It will also enable more effective and efficient use of resources, and help to realise the po ential for increased contributions from public and private funders and individuals.

The vision and high level strategy, and actions set out in this document, are jointly owned by the organisations that have been working together towards the UK Science Partnership for Animal and Plant Health. The have been developed through a series of workshops and consultations with a wide range of stakeholders including government departments, the Devolved Administrations, academia, industry, and NGOs, whose time and contributions are gratefully acknowledged. They are designed to guide the appropriate alignment of strategies[2] and engagement with other key stakeholders towards realising the vision. Actions and deliverables are framed at a high level, and a next step will be for the Partnership to develop a more detailed action plan, identify areas of initial focus, and initiate pilot scale actions. The strategy and key deliverables will need to be evaluated in due course, to identify progress made and assess the impact of new research approaches, tools and technologies on strategic priorities.

Scope and Definitions

UK interests in animal and plant health span a wide range of industries and stakeholder groups. In this document, the terms *agriculture* and *farming* include aquaculture, horticulture, and forestry/woodland management. It is also recognised that these sectors sit within wider managed and semi-managed environments (both rural and urban), and that there are complex and critical interactions between these environments and the wide range of benefits and services they provide to UK society, all of which are influenced y animal and plant health issues.

[1] https://www.gov.uk/government/publications/animal-and-plant-health-in-the-uk-building-our-science-capability

[2] For example, informing Defra's 25-yr F*ood and Farming Pla*n, which is currently under development: https://www.gov.uk/government/news/great-british-food-and-farming-plan-events-held-across-the-country

The strategy encompasses endemic and exotic pests and diseases of plants and animals, including trees, pollinators, finfish and shellfish in aquaculture and zoono diseases. It also includes agricultural weeds. Nutritional and some environmental (for example, invasive non-native species) challenges related to animal and plant health are out of scope, as are research challenges of primary relevance only to the companion animal veterinary sector.

II. THE CHALLENGE FOR THE UK - WHY NOW?

There are many animal and plant pests and pathogens threatening the UK[3], and compelling economic, social, environmental and human health drivers demanding more effective national response within agriculture and the wider environment. The UK needs a more effective and efficient approach to horizon s anning and risk assessment, detection and management options, and methods for mitigating impacts. It also needs to develop more biological, economic and environmental resilience to pest and pathogen challenges.

New knowledge, tools and technologies are providing exciting opportunities to tackle these challenges in innovate ways and to realise sustained, long-term benefits. Ho ever, effective action requires better *whole system* coordination of national scientific aims, resources and apabilities, across stakeholders and disciplines. There are considerable opportunities for new efficiencies and added alue from considering and prioritising animal and plant health science needs together, and from, better aligning and sharing resources, where appropriate, at national and international level. It is now timely to create a national animal and plant health platform within UK agriculture that could also be linked to, and utilised for, environmental monitoring.

The UK Science Partnership for Animal and Plant Health will enable UK stakeholders to more effectively leverage past investments in plant and animal research and development (R&D), including investments in support of the *UK agricultural technologies strateg*[y4], and national strengths in data informatics and analytics[5]. This will ensure the UK maintains its position at the forefront of pest and pathogen detection, analysis and precision treatment, and prediction of pest, disease and weed threats. It will also enable the development of new solutions to the challenges of maintaining a sustainable food supply and thriving countryside.

[3] For example, over 750 pests and pathogens are recorded on the Defra Plant Health Risk Register: https://secure.fera.defra.gov.uk/phiw/riskRegister/

[4] https://www.gov.uk/government/publications/uk-agricultural-technologies-strategy

[5] Including, particularly, the £11.8M AgriMetrics Centre that opened in October 2015, funded by Government through Innovate UK under the UK Strategy for Agricultural Technologies.; also, for example, the Economic and Social Research Council's big data investments.

Key drivers of UK animal and plant health science

Economy

- The global need to produce more agricultural outputs (on less land) requires an intensifi ation of production. There is also little scope to sustainably increase captured fishery productivity so increasing demands must be met y an expanding aquaculture sector. This brings the potential for increased risk of plant and animal pests and diseases, with impacts on productivity and animal welfare, in addition to the need to further enhance productivity by reducing the existing burden of problems.
- The expanding and changing patterns of global trade potentially increases the likelihood of invasive organisms crossing borders. There are also pressing economic, plant and animal protection and animal welfare needs for more effective management of endemic and exotic problems.
- Resistance is developing in pests and pathogens to existing drugs and pesticides.
- A reduction in new drugs and chemical protection products coming to market and increased regulation of control measures within Europe.
- The valuable rural economy, which includes farming, forestry, fisheries, aquaculture, tourism, and the equine/ acing industries, is heavily dependent on healthy livestock and plants:
    - the annual economic contribution (GVA) of these industries is estimated to be over £10bn and the wider agri-food industry, 'from field to ork', adds around £103bn each year (2013)
    - the UK exported £18.8bn of food, feed and drink in 2014 and is one of the top 12 food and drink exporters worldwide
    - the UK imported £8.7bn and exported £0.9bn of fruit and vegetables in 2014
    - the UK is one of the largest importers of wood and timber based products in the world (£7.2bn, 2014)
    - there are 3.8m people employed in the food supply chain, including agriculture and fishing, and many more employed in the wider rural economy.

Environment

- Climate change, the increasing frequency of extreme weather events, and other environmental stresses escalate the potential for new or changed pests, toxins and pathogens to emerge and survive in the UK. This increases stress on natural capital and the provision of ecosystem services, and reduces the ability of UK animals and plants to resist health challenges.
- Negative impacts of poor animal and plant health on agricultural production have environmental costs due to reduced resource efficiency and increased was e.
- The UK's native biodiversity and ecosystems must be protected and sustained.

Society

- Society expects the UK to promote and defend a safe, affordable and nutritious food supply.
- The countryside, coast and green spaces in urban environments are important for recreation and general health and wellbeing.
- Benefits and costs of plant and animal health need to be bet er understood so that they can be more efficiently and equitably shared between public and private interests.

III. A VISION FOR UK ANIMAL AND PLANT HEALTH RESEARCH

In order to effectively respond to the key drivers of animal and plant health science described above, a shared science vision is needed to guide UK investment and alignment of resources:

By 2020, the UK will have created and harnessed new research knowledge and technology that will transform our ability to:

- **systematically predict, detect and understand key current UK animal and plant health problems and emerging threats in real time;**
- **direct sophisticated and rapid responses to effectively and efficiently prevent and mitigate impacts on our agri-environment and wider ecosystems and landscapes.**

In parallel, it will have created the optimal innovation environment for developing and trialling new interventions, stimulating inward investment and the development of new products and services through small and medium-sized enterprises and large national and multinational companies.

This vision can only be delivered through effective partnership working to align priorities across the full spectrum of contributors and effectively manage resources (research funding, facilities, infrastructure, technologies, tools, knowledge, expertise and skills). To realise additional value and avoid 'silos' or duplication of effort this must include key principles of working, catalysed by the UK Science Partnership for Animal and Plant Health:

i. Increased cooperation, collaboration and coordination between:

- **UK policy makers and science funders** (e.g. Research Councils, Innovate UK, Defra and other Government departments, Devolved Administrations, academia, industry and the third sector - NGOs and charities). Technology companies and small and medium-sized enterprises (SMEs) have a big role to play in surveillance and diagnostics together with Innovate UK and regional enterprise organisations. Increased knowledge exchange and coordination is needed between all sectors, and end users and other beneficiaries should also be engaged at the outset to ensure efficient rou es to impact are developed from the start.

- **Leading academic institutions and research groups**. There is a need to build interdisciplinary leadership teams that are able to successfully compete for funding, and to develop capability by utilising existing networks to share knowledge and resources.

- **The UK and key international partners**. Research capability, regulation, and pest-pathogen problems and threats have a strong global dimension and there are opportunities to maximise international engagement, networking, and funding collaboration. This will facilitate the identifi ation of common risks and priorities, and the sharing and combining of national resources to augment capabilities and minimise potential duplication. It will also be essential to engage and influence EU and in ernational regulators to ensure the informed development of risk-based regulatory frameworks that will enable innovative solutions to be evaluated and used effectively for the benefit of the U [6].

[6] The need for risk-based approaches to regulation is discussed in the GCSA's 2014 report - Innovation: managing risk, not avoiding it: https://www.gov.uk/government/publications/innovation-managing-risk-not-avoiding-it

ii. Enhanced communication and public engagement to encourage culture change and best practice. Effective communication with all stakeholders will be essential, to:

- raise awareness of animal and plant health challenges, and the value and potential implications of research developments, and

- identify and respond to public attitudes and concerns, e.g. to encourage public debate on novel technologies and new vaccines/drugs/agro-chemicals.

The potential of citizen science requires greater exploration, in combination with creating the environment and tools needed to engage and mobilise the public in helping to tackle plant and animal health challenges.

IV. BUILDING ON EXISTING UK CAPACITY

UK plant and animal health and animal welfare research is recognised as world leading. The UK is a global leader with a broad base of existing strengths in basic bioscience across the animal, plant and microbial sciences, and in enabling biotechnology, including genomics, informatics, pre-breeding technologies and diagnostics. For example, the UK is pioneering next generation genome sequencing technologies that will enable the identifi ation of pathogens in the field.

However, there are challenges and weaknesses that need to be addressed. Resources are distributed and sometimes fragmented, with a lack of high-level coordination across public, NGO/charity, private and public-private research efforts. This includes, notably, a lack of integrated and aligned research strategies and a lack of agreed data standards across animal and plant health sectors. In some areas community capacity is also lacking. For example, the UK has a strong engineering base, but public funding for agricultural engineering research is more limited; likewise, there is strong disease surveillance capability in the human sector, but less investment in animal and plant health surveillance. There are also key skill areas where UK capability could be limiting for a robust and balanced skill base – in areas such as applied crop/ tree and veterinary pathology, for example. The UK Science Partnership for Animal and Plant Health will work to substantively address these issues.

There are opportunities to better apply a wide range of knowledge, skills and resources to animal and plant health research challenges. This includes UK strengths in social and environmental sciences, economics, engineering, computational and mathematical approaches, satellite (including Earth observation) and meteorological resources, and technologies developed for other sectors. More effective integration of socio-economic thinking and tools into science research, for example, will inform the prioritisation of research targets and improve knowledge transfer and effective uptake of research. There is also a need to better translate applicable knowledge from human health sciences to the animal and plant fields and to realise the mutual benefits of 'on health' approaches across human health, animal health and environmental research investments.

Interdisciplinary, systems and public-private partnership approaches are needed, more broadly, to enable the full range of UK research capabilities to be integrated and to deliver maximum impact. This will drive a better understanding of fundamental science and the underlying causes of problems and spark creative thinking to develop new innovative products and services. Approaches that can link animal and plant health systems at different levels (e.g. from 'field to arm to landscape'), where appropriate, will lead to a better understanding of trade-offs and system tipping points, encourage best practice, minimise negative impacts and capitalise on benefits. This will d velop a stronger focus on effective solutions and policy implications and interventions.

V. CATALYSING THE STEP CHANGE: THE UK ANIMAL AND PLANT HEALTH INTERNET OF THINGS

There are a number of converging opportunities for the UK to develop a 21st Century integrated, scalable infrastructure for ensuring appropriate animal and plant health safeguards through pest and disease management. The emerging *internet of things*[7] provides the basis to seek to develop and establish, in effect, a UK Animal and Plant Health Internet of Things (UK-APHIoT) that can transform our ability to identify and respond to key problems and threats to the agri-environment in a sophisticated way, using the latest technologies.

The UK-APHIoT will catalyse the development of 'next generation' national research capability and improve the impact of world-class research. It will drive a step change in effective translation of research and evidence-based decision making by farmers and other practitioners to predict and mitigate risks at an early stage. It will also provide a platform for technology development and testing by industry, stimulating inward agri-tech investment to the UK and underpinning the global export of these technologies.

Converging Opportunities Underpinning a UK Animal and Plant Health Internet of Things (UK-APHIoT)

- The increased availability of diagnostic and analytic technologies, many of which have yet to be fully deployed in an agricultural setting, providing new capabilities to detect, analyse, understand and respond precisely to an increasing range of health threats, including pests and pathogens.
- The internet of things and increased capacity for device-device and user-user communication provides the potential underpinning infrastructure to build agri-tech connectivity and interoperability across technologies and different scales, from the farm and field to the region or national resources. onsiderable spectrum band-width has recently been freed up and is ripe for exploitation. These ideas are explored more generally in the GCSA's 2014 review of the Internet of Things.
- The UK already has data-rich resources for environmental/landscape observation and monitoring that is publicly available in increasingly accessible and assimilated forms.
- The UK contains some of the leading research centres for plant and animal health globally. Facilitating the pipeline for translation will signifi antly increase the UK's attractiveness to multinational industries as a place to commercialise and trial new interventions.
- Multinational inward investment is already high, with the potential to grow, and new sectors are investing in agri-tech and food security.
- The UK has a vibrant and growing SME community in the agri-tech sector, and other key areas such as digital technology and the medical diagnostics sectors, that could signifi antly contribute to, and benefit rom, invigorated UK capability in pest and disease surveillance, analysis and intervention.
- At a local and regional level, signifi ant opportunities exist to enhance efficiency and cost-ef ectiveness of current interventions.

[7] The network of physical objects or "things" embedded with electronics, software, sensors, and network connectivity, which enables these objects to collect and exchange data. The concept is explored succinctly in this McKinsey Insight article: http://www.mckinsey.com/insights/high_tech_telecoms_internet/the_internet_of_things. The UK Government Chief Scientific Adviser's report to go ernment in December 2014 also highlighted the economic potential of the Internet of Things to the UK economy and government, and making a series of recommendations to maximise the opportunities and reduce the risks for these new technologies.

At the heart of the UK-APHIoT would be a web which will flexibly interconnect sensors and data nodes to enable much earlier and more sophisticated detection of pests and pathogens on farms and within the wider environment. This will integrate established regional and local surveillance infrastructures and allow distributed, crowd-sourced data inputs to be plugged in, alongside data from wider sources - for example, robotics and semi-autonomous devices with 'smart' management systems, meteorological, geological and Earth observation. Combined with appropriate modelling, and 'big data' tools enabling effective management, evaluation and translation, this will provide:

- comprehensive evidence to identify priority pest and pathogen problems and risks
- reference databases to enable farmers and other resource managers to make informed local and regional decisions
- evidence to inform national policy, commercial and research decision making
- a fertile test bed for new diagnostics and interventions, and
- an enhanced capability to assess the benefits and risks of crop and animal breeding echnologies.

To remain relevant over the longer term, the UK-APHIoT must be dynamic - able to modernise and integrate new technologies and research approaches as they develop, adaptable to changing pest and pathogen challenges and responsive to new developments in the industry sector.

The UK is well placed to deliver a UK-APHIoT with regional elements: the UK has a world leading bioscience research sector, is a global supplier of plant and animal genomic technologies and has the world's best architecture for combining meteorological and environmental data. The UK also offers a unique variability of climate, soil types and land management systems, and therefore has 'mini agri-environments' that can be translated to agricultural systems in other countries. There are also emerging technologies being developed in the research base, SMEs and across the innovation landscape in the UK.

There are, however, challenges to be addressed in driving forward its development:-

- Some of the individual components of such a platform already exist, but resources and data are often held in isolation by different organisations and not shared. There are likely to be data protection and governance challenges in sharing some datasets.
- Resources are limited, and an effective modular approach towards realising an ambition of integrated capabilities will be required as well as learning from other sectors that are investing in corresponding *internet of things* capabilities.
- Pest and pathogen detection technologies have advanced signifi antly, but current surveillance strategies often rely on older, well established methodologies, in most cases requiring manual sample collection and centralised analysis. There is a need to 'pull through' these advanced approaches.
- Emphasis is needed on development of an appropriate base of skills and expertise to achieve this ambition, bringing together a wide range of science and technology research disciplines.
- There is a need to provide the UK with the latest field-ready ech to enable real time data acquisition; fully utilising crowd sourcing to provide an army of data acquirers, e.g. through phone apps and wearable technology.

- There is a need for an effective framework and resources for management, integration, analysis and interpretation of different 'big data' types. Combined with systems based modelling to enable the effective extraction and synthesis of key data for interpretation and use by researchers, policy makers and practitioners.

- There is a lack of unified da a standards and interoperability across the surveillance and detection technologies used in animal and plant health sectors.

- There are limited incentives for uptake of new techniques and technologies and a lack of clearly identified areas for precompetitive public-private research investment. End-user investment will need to be incentivised, addressing market failures and barriers to uptake; e.g. short-term cost considerations stifling longer- erm benefits realisation, and the ension between 'public good' benefits and commercial profitability.

- While the UK has a well-developed strategy to assess and tackle the threats posed by invasive non-native species, increasing globalisation and the EU Single Market drive the need for greater multi-national cooperation.

- Evidence-based decision making will require farmer/practitioner/citizen understanding and appreciation of the value of UK-APHIoT. This will require signifi ant engagement and facilitation, and understanding/mitigation of potential social barriers to success.

Pilot scale development and testing of a UK-APHIoT concept will allow these challenges to be systematically addressed. A key requirement of such a data-rich area is the harmonisation and standardisation of data and protocols. To achieve this it will be important to pilot the robustness of technologies in different field conditions, gene ate pilot data to populate models and beta-test the tools and software to ensure data interoperability. Piloting the UK-APHIoT will also give SMEs, researchers, policy makers and practitioners the time and tools to explore innovation opportunities and the commercial potential of novel technologies, and to consider issues of scalability.

It will be essential to pilot the UK-APHIoT in more than one exemplar region. The UK has very diverse ecosystems and land management systems, providing a wide variety of services under different environmental conditions, and with different animal and plant health challenges. Regional pilots spanning signifi antly different environments and building on existing infrastructure will enable the development and testing of modular approaches, and for challenges to integration and scalability of regional elements to be considered and tackled. For example, regional pilots could be focussed in the East and Southwest of England, where high crop yields and lowland dairy farming are, respectively, under threat from numerous pathogens and pests, and upland environments such as those in Scotland, Wales, Northern Ireland and Northern England, where livestock farming, forestry and environmental factors and sustainability pressures dominate.

ACTION 1: The new UK Science Partnership for Animal and Plant Health will establish the framework and operating pilots for a UK Animal and Plant Health Internet of Things, which will:

- enable fast, systematic detection, analysis, understanding and prediction of animal and plant health risks
- direct the timely application of the most effective interventions and facilitate their uptake, and
- protect and strengthen the UK's rural and land use economy and stimulate inward investment by industry.

VI. KEY RESEARCH PRIORITIES

Key public research investors must prioritise collaborative research themes in order to successfully deliver the vision. The UK-APHIoT will enable a step change in research capability and the ability to effectively translate and realise the benefits of research. orking within this framework, it is also necessary for the UK Science Partnership for Animal and Plant Health to identify clear research priorities to:

- coordinate and build on existing UK strengths in essential frontier research, and capitalise on the potential of 'next generation' systematic and trans- and interdisciplinary research approaches
- develop new tools and technologies, and the scientific and social in rastructure, to enable their effective use, and
- develop integrative approaches to collect, assimilate and analyse evidence to monitor, model and manage the impacts of animal and plant health challenges.

Three key research themes have been identified, with associated deliverables for success. These deliverables have components that are applicable over short, medium and long-term timescales. With concerted action, some challenges can be addressed within a fi e year timeframe. However, a sustained long-term focus on developing and maintaining coordinated national capability in these theme areas will be essential to meet the dynamic challenges posed to animal and plant health, and deliver associated economic growth and social and environmental wellbeing for current and future generations of UK citizens.

THEME I: Improved understanding of current and emerging pathogen and pest threats and how they may be controlled – *growing and maintaining world class interdisciplinary science capability*

Fundamental bioscience will provide the essential wellspring of new knowledge and skills to drive breeding for disease resistance and resilience, development of strategies to reduce pathogen and pest resistance to control measures, development of next generation control options, and new diagnostics and sensors for better surveillance and risk registers.

Prioritisation must be informed by agri-environmental economics research (e.g. taking into account the cost of losses from particular diseases - including impacts on wider ecosystem services - vs the cost of disease control strategies). Social science approaches are also required at the outset to address the understanding, acceptance and use of new technologies, and to incorporate systems for their effective translation. Priorities must also be informed by key policy requirements and value for money considerations, and the need for UK research capability that can respond flexibly to emerging needs and threats.

THEME I - DELIVERABLE 1: To develop more systematic understanding of i) pest and pathogen biology and diversity, including ecology, evolution and transmission dynamics, and ii) pathogen-host interactions, including host immune responses.

A focus is needed on enabling more proactive pathogen identifi ation and mapping and understanding of the selective pressures that drive emerging threats, disease susceptibility and antimicrobial resistance. This includes including understanding the role of, and key interactions with, disease vectors, and the impacts of human behaviour and climate change. 'Diagnostic gaps' also need to be closed, where causal agents of disease syndromes are unknown or where discriminating technology is lacking, to effectively identify and track newly emerging pathogens.

These aims will be substantially enabled by the integrative 'big data' collection delivered by the UK-APHIoT by underpinning systematic analysis of pathogen and host genomes and their interactions, including a focus on novel identifying pathogen effectors and understanding host immunity and mechanisms underpinning intervention responsiveness and effi acy (including animal vaccines).

THEME I - DELIVERABLE 2: To accelerate breeding for sustainable resilience and resistance

Systematic breeding is required to enhance overall health resilience and broad-spectrum pest and disease resistance in key crops, trees, and farmed animals. This requires a better understanding of the underpinning biological mechanisms of, and markers for, these complex traits. Priority investments will include generic breeding tools and technologies, including 'omic' technologies to improve marker assisted breeding. This will increase the UK's ability to improve agricultural productivity and to improve animal welfare by reducing the burden of existing problems, and adapt to the withdrawal of key control agents (e.g. driven by EU regulations on pesticide usage and reductions in the use of anti-microbials for food producing species). It will also accelerate the UK's ability to respond effectively to new pest and pathogen introductions and emerging threats.

Public investment is particularly important in areas where there is market failure, and clear routes to commercialisation need to be identified. rade-offs - such as negative correlations between disease resistance and other economically important traits - must also be understood, and addressed, if new breeding programmes are to produce commercially viable and sustainable outputs.

THEME I - DELIVERABLE 3: To reduce the impact of anti-microbial, anti-parasitic and pesticide resistance in pathogens and pests of animals and plants

The development of resistance in pathogens and pests to chemical controls poses a risk to food security and public health, as well as negatively impacting animal welfare. Better understanding is needed of the impact of current policies and behaviours relating to antimicrobial, anti-parasitic and agrochemical use in plants and animals, particularly in farms and their associated environments. Their role in the development and propagation of resistance (including propagation in, and interactions with, the wider environment), and how available tools can be used more effectively to minimise this risk also needs further clarity. The latest techniques must also be applied to detect resistance and understand the mechanisms leading to its development and propagation. Interdisciplinary approaches will underpin both the development of novel antimicrobials (including anti-helminthics) and other intervention strategies, and the responsible use of these tools to achieve sustained effi acy[8].

THEME II: New technologies to detect and control pest and pathogens – *enhancing the UK's ability to develop, validate and use them*

New technology will be essential to enable the UK to effectively respond to current and future animal and plant health challenges. This includes preventing or reducing losses from pest and disease outbreaks and spread, and also enhancing value by reducing the current 'steady state' burden of widespread problems. This will necessitate interdisciplinary research across bioscience, physical, environmental and mathematical sciences and engineering, and social and economic research, particularly in areas such as 'omics' technologies, bioimaging and sensor technology, as well as tools to collect, handle and interrogate new and existing data. There is also a

[8] A cross-Research Council tackling antimicrobial resistance initiative is targeting current and future investment across key themes identified y the AMR Funders Forum, and activities will need to be joined up appropriately. https://www.mrc.ac.uk/research/initiatives/antimicrobial-resistance/tackling-amr-a-cross-council-initiative/

need to repurpose existing technology developed in other industrial sectors, and to incorporate learning from work investigating the development and application of state-of-art detection and monitoring technologies for environmental research[9]. The demand for these tools is cross cutting and there are clear benefits to be deri ed from a coordinated, collaborative approach to their development and application.

THEME II - DELIVERABLE 1: To develop and apply new technologies for faster, more sensitive and more efficient detection of pests and diseases

Novel tools and technologies are required to drive a step change in capabilities (including the availability, efficiency and cost effectiveness of these tools) to detect and monitor important pests and diseases, including at national borders and where appropriate within import/export regulatory frameworks.

These include:

- developments in remote sensing (e.g. Earth observation, mobile and fixed tools);
- integrated and automated systems;
- data management, handling and analysis;
- statistical techniques;
- population databases;
- diagnostic tools, methods and kits, including non-destructive tests; and
- novel software, and other surveillance tools such as unmanned aerial and marine vehicles, satellites and sentinels.

Creating the infrastructure for the systematic deployment and interoperability of these tools presents a particular challenge and provides an opportunity for pilot-scale work towards developing the UK-APHIoT (linking to the development of integrative surveillance capability: Theme III – Deliverable 1), engaging with and drawing upon existing platforms for environmental observations[10] and data standards[11].

New tools and technologies, that allow data to be captured and utilised in real-time, will enable decision makers (both policy and industry) to detect changes in disease patterns or emerging pathogens far, more quickly than is currently possible, and to make rapid, evidence-based policy and interventions at the appropriate level (e.g. farm/ land management unit, region, nationally).

THEME II - DELIVERABLE 2: To improve and create new technology platforms to combat endemic and emergent pests and diseases

New and improved platform technologies are required to underpin the development of effective new intervention strategies that could be tailored and applied to a broad range of pests and diseases. This includes developing innovative approaches to tackling the problems caused by resistance to pesticides, and herbicides (for weed control), or increasing regulatory restrictions to their use.

For animals, vaccination is one of the most cost effective long-term disease control strategies and offers the possibility of eradication. Research to enable the development of effective 'next generation' vaccines is required, including for non-viral pathogens, as are corresponding interdisciplinary approaches to ensure their effective

[9] For example, miniaturisation of 'omics technologies for field-based appli ations: http://environmentalomics.org/omics-miniaturisation/

[10] For example, the Satellite Applications Catapult's Climate, Environment and Monitoring from Space facility: https://sa.catapult.org.uk/cems

[11] For example, the UK Environmental Observation framework Data Initiative: http://www.ukeof.org.uk/our-work/data-initiative

deployment. This will reduce the reliance of the UK livestock industry on antimicrobial, anti-protozoal and anti-parasitic agents, and will improve animal welfare and reduce the economic burden of disease, thus leading to an increase in UK agricultural productivity. To achieve this will require the effective development of vaccine technology platforms and improved underpinning bioscience knowledge, including a better understanding of host immunity and immune escape (linking to Theme I - Deliverable 1). It will also require the development of novel tools and technologies to produce vaccines that are effi acious, thermo-stable, cost effective, easy to administer and traceable. *Differentiating Infected from Vaccinated Animals (DIVA)* technology will offer the prospect of protected international trade, and must inform EU and trade regulations, through effective engagement with international bodies.

THEME II - DELIVERABLE 3: To develop new field tools to guide precision interventions

Tools are required to enable rapid, precise and specifi ally targeted interventions when animal and plant health issues are identified. This includes sensor echnology to precisely direct the administration of medicines to livestock, using knowledge gained from immunology and subclinical biomarkers, and chemical treatments or other plant health controls on farms and in the wider environment. More sophisticated surveillance approaches (link to Theme III, Deliverable 1) will guide fast precision interventions at appropriate scales of deployment.

More focused and integrative usage of antimicrobial/anti-parasitic agents and agrochemicals will provide the ability to precisely control pests and pathogens, and reduce both environmental impacts and the chances of resistance developing. This is especially important in the face of the loss of control agents due to tighter EU legislation, and will potentially deliver financial s vings to farmers and other land managers - a key driver for effective research translation.

Portable, robust and user-friendly biosensors will offer in-field 'point-of- are' diagnostics to ensure correct usage of antimicrobials or chemicals, and will assess the prevalence of resistance to them. New surveillance technologies will also facilitate more sensitive and systematic monitoring of pest and pathogen populations and their changing distributions, including invasive threats.

Integrative research approaches will be required to identify and develop these tools so they meet key user needs and can be effectively taken up and applied.

THEME III: Integrative approaches to monitor, model and manage endemic problems and emerging threats – *guiding precision intervention at local and landscape levels*

Landscapes are complex systems and a more coordinated, multi-scale and inclusive approach is required to monitor, model and manage the impacts of animal and plant health challenges on them, and on the services they deliver for UK productivity and wellbeing.

THEME III - DELIVERABLE 1: To develop next generation, integrative surveillance capability for animal and plant health

A step change in effective surveillance capability is required, from the individual plant or animal, to farm/water body, landscape, national and international levels. Data from a dynamic and evolving landscape must be captured and integrated into a real time surveillance system to detect and track endemic and emerging diseases, and to support trade by inspecting more effectively at the border and in-land.

This includes the monitoring of spatial and temporal distribution of hosts (livestock, crops, wildlife, unmanaged plant species) and pests and disease vectors, providing proxy information about the transfer of potential disease

agents. It also includes incorporating monitoring of soil, fresh and marine water and air, linked with meteorology, to better understand and predict important environmental factors for animal and plant health. Greater integration of UK surveillance networks and effective links between UK and global surveillance programmes are both required to avoid duplication and make best use of resources.

There is a particular challenge in appropriately capturing, managing and effectively mining "big data" relating to surveillance. Improved data science capability is required to develop new approaches to storing, synthesising, analysing and sharing data from structured and unstructured sources, and to understand and factor for data biases. This is particularly important for crowd-sourced data. New techniques are needed for data curation, standardisation and communication. This includes research in social behaviour and methods of communication that are effective in influencing decision making. est and disease intelligence must be made more accessible to farmers and veterinarians to inform local action, and to government agencies to enable evidence-based policy making. This will ensure rationalised allocation of resources to tackle endemic problems more successfully, and to allow a rapid response to minimise the economic and environmental impact of a disease outbreak/pest incursion. New approaches to monitoring and detection will also lead to the emergence of new questions and 'unknowns'. It is essential that as new technologies are developed, the appropriate risk assessment systems to support these are also developed.

THEME III - DELIVERABLE 2: To develop more systematic and flexible modelling approaches to inform effective pest and disease management

Combining land use and systems data with an improved understanding of the epidemiological processes propagating pests and diseases through the system will enable us to understand existing baselines. It will also help to understand the consequences of changing patterns of incidence, help identify risk factors, aid the design of rational control/prevention strategies for agricultural systems and the wider environment, and guide the more effective application of detection strategies. This should be linked through to the development of a risk register that builds on existing data and policy evidence, and guides more rational allocation of resources.

Systems approaches provide a powerful tool for modelling of disease transmission and spread of pests, and for prediction of the consequences of external shocks. New models are required that are scalable, able to account for uncertainty, can be flexibly adap ed to a range of pests and pathogen systems, and which are linked to wider land use and meteorological data. This includes factoring the potential impacts of changing human markets (e.g. increases in smallholdings and market gardens or, in contrast, increases in large intensive farms), practices (e.g. organic farming, precision farming, aquaponics, centralisation of slaughter houses) and behaviours (e.g. increased visits by the public to diversified arms or reduction in public access due to heavy forestation). Modelling of complexity on this scale may require the development of new computational tools and methods to incorporate social science data. High quality information from active surveillance networks will be needed to feed into modelling approaches.

THEME III - DELIVERABLE 3: To understand and foster the role of environmental and agri-systems resilience in promoting animal and plant health

The landscape provides a variety of ecosystem services, of which agriculture is one, but also including clean water, biodiversity and protection from natural hazards (e.g. floods and pathogens). It also provides many socie al benefits, anging from physical and mental well-being through to aesthetic, cultural and recreational benefits. There is a need for an interdisciplinary and systems approach to better understand the key components of ecosystems and ecosystem services that may interact to increase or reduce disease and pest burdens and risks, including biodiversity, food webs, natural biological or other environmental control agents and risks. This will require better understanding of reservoirs/transfers of pests and pathogens (and antimicrobial resistance), critical interactions between domestic and wildlife species - and with people (including zoonotic transfers), and the impact of pests and pathogens on the wider ecosystem and derived services, to better predict threats and ecosystem tipping points.

This whole system approach will inform a better understanding of the societal and economic implications of policies and actions to manage animal and plant health, and guide appropriate interventions and incentives that account for impacts on the provision of various ecosystems services. It will enable the development of more holistic agricultural and landscape management approaches that can be implemented effectively by policy makers and practitioners to enhance ecosystem resilience and agricultural productivity, thus reducing the overall burden of endemic pests and diseases and effectively controlling outbreaks.

ACTION 2: The new UK Science Partnership for Animal and Plant Health will prioritise research investment and align strategic agendas and research programmes around three key themes and nine deliverables:

I. Improved understanding of current and emerging pathogen and pest threats and how they may be controlled – growing and maintaining world class interdisciplinary science capability:

- To develop more systematic understanding of i) pest and pathogen biology and diversity, including ecology, evolution and transmission dynamics, and ii) pathogen-host interactions, including host immune responses.
- To accelerate breeding for sustainable resilience and resistance.
- To reduce the impact of anti-microbial, anti-parasitic and pesticide resistance in pathogens and pests of animals and plants.

II. New technologies to detect and control pest and pathogens – enhancing the UK's ability to develop, validate and use them:

- To develop and apply new technologies for faster, more sensitive and more efficient de ection of pests and diseases.
- To improve and create new technology platforms to combat endemic and emergent pests and diseases.
- To develop new field tools to guide precision in erventions.

III. Integrative approaches to monitor, model and manage endemic problems and emerging threats – guiding precision intervention at local and landscape levels:

- To develop next generation, integrative surveillance capability for animal and plant health.
- To develop more systematic and flexible modelling approaches to in orm effective pest and disease management.
- To understand and foster the role of environmental and agri-systems resilience in promoting animal and plant health.

Working within the framework of the proposed UK Animal and Plant Health Internet of Things, this strategic approach will deliver the next generation of capability, knowledge and technologies required to predict, detect and understand problems, and protect and enhance animal and plant health.

VII. NEXT STEPS

The vision and high level strategy, and actions set out in this document, will be jointly owned by the organisations that make up the UK Science Partnership for Animal and Plant Health, and will provide the high level research framework to appropriately align funding strategies and to engage with other key stakeholders to work towards realising the vision. The next step will be for the Partnership to develop a more detailed action plan, and identify areas for improved collaboration and co-ordination across the Partnership. Scoping work will be initiated, as a priority, on potential regional pilot scale activities to further explore the opportunities and challenges presented by the proposed UK-APHIoT.

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