Institution: Queen's University Belfast

Unit of Assessment: UOA6

1. Context, structure and strategy

a. Overview

Since 2014, the **Institute for Global Food Security (IGFS)** has played a leading role in developing solutions to the complex problem of ensuring access to safe, nutritious, sustainable and authentic food. IGFS was designated one of three Global Research Institutes (GRIs) within the University in 2016, in an initiative to support world-leading research and bring researchers from different disciplines together on a scale that enables them to address major societal challenges. IGFS is embedded in the School of Biological Sciences (SBS) with links to the School of Medicine, Dentistry and Biomedical Sciences (SMDBS) and other schools. Since 2014, IGFS has attracted significant investment and our academic staff have more than doubled from 33.4 to 72.8 FTEs.

Global population growth, climate change and the double burden of undernutrition alongside obesity necessitates the need to fundamentally transform global food systems. This places healthy people and a healthy natural environment at the core of transforming food systems. Our distinctive strengths map onto the United Nations (UN) sustainable development goals and fit with the global focus on the importance of food for health, exemplified by the 2019 EAT-Lancet commission report which highlighted food as one of the greatest health and environmental challenges of the 21st century.

Culture of impact and innovation We have grown our impact culture substantially since 2014 and have embedded a team of impact champions, including Early Career Researchers (ECRs) and senior staff within the Institute. IGFS's inclusive research philosophy promotes cross-fertilisation which occurs as a result of researchers from different disciplines working together to exchange and share their distinct approaches, facilitating a step-change in the scope and reach of IGFS research, driving impact at local, national and international levels. This approach to food security is transformational, with beneficial impacts on policy, society and industry. Key examples include the Elliott Review on the Horsemeat scandal, development of the world's only vaccine for porcine wasting disease and determining the impact of intensive animal farming on climate change and land use. Recently, the UN International Atomic Energy Agency (IAEA) designated IGFS as an IAEA Collaborating Centre, recognising its global reach in food safety, authenticity and traceability.

Infrastructure investment Completed in 2019, a new 12,000m^2 £39M state-of-the-art research facility, accommodating 500 research staff/students, demonstrates the University's commitment to IGFS, maximising interaction and reinforcing the drive towards interdisciplinary research (IDR). Further investments across the IDR pathway include the Assured Safe and Traceable (ASSET) technology centre (now designated a 'Centre of Expertise' by the Food Authenticity Network (Department for Environment, Food and Rural Affairs (DEFRA)), a leading analytical chemistry/mass spectrometry research hub (£10M), specialist proteomic and biosensor facilities (£2.5M), and a dedicated research facility investigating innovative technology to reduce chemical and antibiotic use in the food chain (AgriPlas), the first of its kind in Europe (£0.4M). Our partnership in the planned Global Innovation Institute (GII) (£60M investment as part of the Belfast City deal, 2021-36) provides us with an unparalled opportunity to apply digital technologies to further address major societal challenges in health, food security and environmental sustainability.

Research Growth We have increased by 39.4 academic staff in this REF2021 submission (including senior strategic appointments in systems biology, digital innovation, global change biology, nutrition and preventive medicine, food integrity and 10 ECRs), organised across our four challenge-driven research themes. Over the reporting period, IGFS has secured £59M

research investment from diverse sources, including EU, UKRI, National Institutes of Health USA (NIH) and Science Foundation Ireland (SFI), a 3-fold increase since REF2014, resulting in a concomitant rise in Post-Doctoral Research Fellows (PDRFs). We have graduated 248 PhD students relative to 84 in the previous reporting period (a 3-fold increase). Furthermore, the award of two cohort-based doctoral training programmes (DTPs; UKRI-BBSRC, UKRI-NERC) (see section 2e) since 2014 ensures we are leading the way in training the next generation of food system leaders.

Academic success Since 2014, IGFS staff have published 3,121 research outputs which have received 52,040 citations across 197 countries. The outputs have recorded a Field-Weighted Citation Impact of 1.80, well above the world average of 1.0. Of these outputs, 69.7% were published in the top quartile of journals (as ranked by SNIP) and 26.8% are included in the top 10% most cited papers in the world. The strong international collaborative linkages are evidenced by the international co-authorship: from 2014-20, 66.3% of all IGFS outputs included an international co-author (Russell Group average – 55.1%). We collaborate with world-leading research institutions including: McGill University (Canada), the Chinese Academy of Sciences (China), the University of California (Davis and Berkeley; USA), Broad Institute (USA), Harvard TH Chan School of Public Health (USA), Institute for Agrobiology (Austria), University College Dublin (UCD; Ireland), Ghent University (Belgium), Wageningen University & Research (WUR; Netherlands).

Embedded interdisciplinary research (IDR) IGFS encourages IDR and innovation, teaching and enterprise that links the disciplines of life sciences, medicine, environmental sciences, economics and social sciences, working with key stakeholders, including industry, to deliver on key challenges in Global Food Security. The breadth and depth of IGFS has accelerated since REF2014, with connections strengthened between the SBS and SMDBS and new links built with the Schools of Pharmacy and the Natural and Built Environment, as well as our sister GRI, Electronics, Communication and Information Technologies (ECIT). In 2019, IGFS appointed a Director for IDR to further IDR approaches to complex issues in food systems.

b. Organisational structure, size and context

The Institute is led by Professor Nigel Scollan, with management overseen by a 10-member Management Board (MB) including the Director, Head of SBS, Deputy Director, Director for IDR, 4 theme leads, Director of Internationalisation and a Director of Innovation. IGFS is supported by an Institute Manager and an administrative support team, Events and Campaign Co-ordinator and a Stakeholder Engagement and Communications Officer. The MB develops research and impact strategy and reports to Faculty and the Pro-Vice Chancellor for Research (PVC-R). IGFS strategic development is guided by an International Scientific Advisory Board (ISAB) and an Industrial Advisory Board (IAB).

IGFS is organised into four challenge-driven themes (Figure 1; Food Integrity, Nutrition and Preventive Medicine, Agriculture and Environmental Resilience, with a newly introduced cross-cutting theme of Enabling Technologies, Data and Digital Innovation), each with a critical mass to deliver transformative IDR. Each theme is led by a senior academic and co-led by an ECR, appointed competitively, to support capacity building and succession planning. These integrated themes allow co-ordinated research, alongside innovation/impact and close-working with policymakers, businesses and other stakeholders.

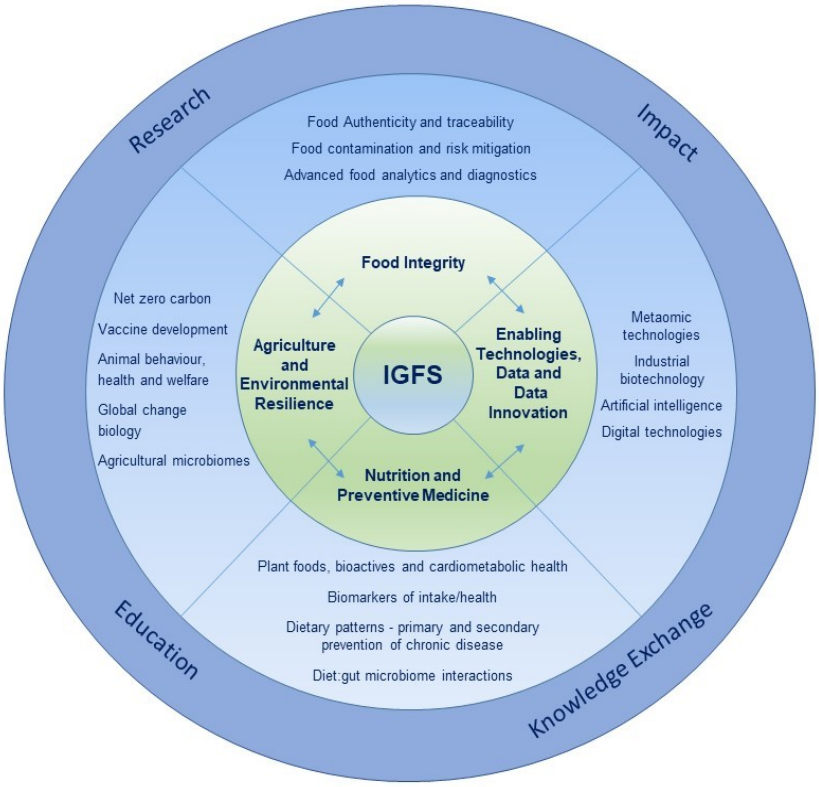

Figure 1. Challenge-driven interdisciplinary research themes in IGFS

c. Research and Impact Strategy

IGFS facilitates a vibrant and integrated research and impact environment, conducting globally competitive and sustainable research addressing major challenges in global food security. The pursuit of academic excellence, the translation of research findings and ensuring sustainability through a concerted focus on 'people' and 'research ambition' aligns with Queen's corporate priority (see s2b). Key achievements since 2014 alongside future strategic plans include:

Key achievements since 2014

- *QUB priority research area* – Strategic, sustained growth and restructuring of IGFS, leading to recognition by QUB as a priority research area in 2016 and establishment as one of three institutional GRIs.
- *Building scientific capacity* – Significant investment in category A staff, growing from 33.4 to 72.8 FTE to consolidate our strengths in food integrity and animal health, grow critical mass in enabling technologies/data innovation, human nutrition, agriculture and environmental resilience and further strengthen research quality, leadership and succession planning. Since 2014, there has also been a substantial expansion in PhDs graduating (a 3-fold increase - 84 to 248). A crucial element of our strategy has also been to foster an environment that attracts talented ECRs, with 10 staff being ECRs (see section 2d).
- *Infrastructure investments* – Recent investments have strengthened the research environment (detailed in section 3b and c), including the new £39M state-of-the-art research facility and the £10M expansion of the ASSET technology centre.
- *Enhancing our enterprise/industry ecosystem* – Development of an enterprise hub to strengthen partnerships and interface with industry, both locally (e.g. £5M Agri-food QUEST Competence Centre), nationally and internationally (e.g. European Institute of Innovation and Technology (EIT) via €400M EIT-Food (see section 3a). In 2016 we constituted an Industry Advisory Board (IAB) to provide strategic input and advice. We have also secured 5 x BBSRC Industry Partnerships and 1 x BBSRC Link award, 13 Knowledge Transfer Partnerships (KTPs) and >18 case-studentships with industry partners.
- *Strengthening engagement with Government* – Exemplified by Elliott, who engaged with both the UK and Irish governments on developing a national food system based on the

principles of food integrity and led the UK government's independent review of the food system following the 2013 Horsemeat scandal.
- *Developing inclusive collaborative team-spirited environment* – Exemplified by both SBS and SMDBS holding SWAN Athena Gold (October 2020). Uniquely, SBS have now achieved Gold on 3 occasions – initial award (2013) and 2 renewals (2016 and 2020).

Future Strategic plans
- *Build additional academic excellence* – foster and facilitate ECRs, grow our DTPs to train the next generation of IDR scientists and appoint and retain high-quality researchers and leaders in our challenge-led themes. IGFS will grow to 90 FTE academic staff over the next five years and strategic appointments will either strengthen current world-leading research activities or build new competencies, allowing us to better respond to global priorities.
- *Further develop IDR* – conduct, catalyse and deliver research which integrates key partners within QUB, across Ireland and together with leaders in academia, industry and policy worldwide to accelerate solutions to societal challenges.
- *Advance existing and additional national and global academic partnerships* - strengthen focus around transforming food systems. IGFS will further employ a truly IDR and innovation agenda. A major focus will be on the island of Ireland as a model of transforming food systems, exemplified by the establishment of a Centre for Food-Integrity, (Food-I*)* (see section 3c)
- *Development of strategic alliances* – exemplified by our partnership with Agri-Food Biosciences Institute (AFBI) in Northern Ireland, and the £30M Austrian Competence Centre for Feed and Food Quality, Safety & Innovation (FFoQSI), seeking to accelerate building and sharing capacity, both in infrastructure and people, addressing key challenges in agriculture and food, and supporting policy, industry and society.
- *Expand and diversify the impact of our research* - further increase the translation of our research to inform policy development, industry and society through the growth of our interactions with industry and the development of longer-term partnerships with multi-national companies, government and society. This is exemplified by our leadership and engagement with EU EIT-Food (see section 3a) and an embedded proactive approach to impact.
- *IGFS is leading in the creation of the "Northern Ireland Diamond"* - integrating and building a partnership ecosystem, in which government, business, society and the knowledge base work together pooling goals, funds, risks, responsibilities and competencies in agri-food. This will underpin innovation, growth, value and impact for the agri-food sector.
- *Continue to develop and enhance our research infrastructure* – We will seek additional investment (public-private) to enhance our research, education, enterprise and public engagement capacity around the new building (see section 3b). We are leading several projects in the innovation strand (£200m) of the Belfast Region City Deal (£1bn) (see s2d, s4c). As an integral partner in GII, this initiative will provide major technological advances, give rise to enhanced expertise in digital technology and afford new opportunities to harness the potential of emerging technologies in agri-food, nutrition and health care. A further £10M will also be invested over the next REF cycle to enhance our clinical trial capabilities (iREACH, see section 3c).

Research themes - selected achievements and future plans (research and impact):

Food Integrity

Consisting of 10.7 FTE academic staff (1 ECR), 21.2 FTE PDRFs, 28 PhD students, this theme integrates diverse expertise in basic and applied research encompassing chemical contaminant detection, food microbiology, fraud detection and food systems traceability and transparency. Key strengths reside in research focused on understanding the health risks of dietary associated food contaminants and the development of novel approaches that can pre-emptively mitigate the impact of these threats on food supply chains. Since 2014 the theme has undergone significant expansion particularly in increasing our capacity in mass spectrometry (see section Enabling Technologies, Data and Data Innovation, below), strengthening our ability to develop innovative

approaches to detect contamination and fraud for industrial and regulatory food control applications.

The renowned excellence of theme members is formalised in over £6M funding from H2020 and BBSRC (Campbell, Cao, Connolly, Elliott, Meharg, Mooney, Williams), allowing development of advanced rapid-screening of high risk microbiological and chemical contaminants through cutting edge technologies and enhancing the understanding of the critical importance of trace element biogeochemistry within food-chains for food safety and health. The theme also houses the UKRI-BBSRC DTP "FoodBioSystems" (£2M IGFS, £6M total, 2020-28) and the EU MONPLAS Innovation training network (€6M, 2020-23). Theme members have also demonstrated major industrial, economic and societal impact, e.g., following the aftermath of the 2013 Horsemeat scandal, Elliott conducted the UK government review (The Elliott Review, which forms an impact cases), leading to a rapid expansion in food fraud and authenticity research activity at QUB and across the UK. Consequently, the team worked closely with industry to develop risk management tools and traceability systems to help mitigate the risks of accidental or intentional contamination and fraud to assure food integrity (Elliott, Mooney). Another example of industrial and economic impact is Food Fortress© (another impact case), a unique risk-based supply chain management tool implemented by over 70 global food/feed companies to ensure food authenticity. The capacity and excellence within this theme is further illustrated by our ability to respond rapidly to emerging priorities, for example, recent funding was obtained from the SFI COVID-19 Rapid Response Funding Call to ensure a resilient food supply, given the challenges of the current pandemic (£0.1M; Elliott). Theme members also have strong collaborations within the EU and international partners based on funded projects and/or co-authored publications, including WUR and Chinese Agricultural University, Beijing.

Nutrition & Preventive Medicine

Our key expertise lies in three main areas: molecular nutrition (Green, Roche, Su), biomarker development and discovery (Green, Woodside, Young) and nutritional epidemiology and randomised controlled trials (Kuhn, Cassidy, McEvoy, McKinley, Woodside). A major research theme focuses on plant-based diets, diet quality, biomarkers and cardiometabolic health, with world leaders at the Harvard TH Chan School of Public Health (Cassidy, Woodside). This work integrates novel analytical approaches and focuses on plant-based diets, flavonoids and a range of health outcomes, including cardiometabolic health/healthy ageing. This theme consists of 14.3 FTE academic staff (4 ECRs), 27 PDRFs, 36 PhD students. Since 2014, there has been a significant expansion in nutrition research, which at that time was fragmented, with staff being returned to UoA2 and UoA6. Nutrition research is now an integral IDR component within IGFS, expanding from six to 14.3 FTE academic staff within the last two years.

The renowned excellence of theme members has resulted in a prestigious US-Ireland R&D Partnership Programme (multi-agency funding including NIH/HRB/SFI/NI R&D Office/MRC; £3.25M; 2019-24; Woodside), exploring whether a panel of biomarkers can capture overall dietary intake/quality. Green was also awarded an US-Ireland R&D Partnership Programme (2019-24; £2.5M), to develop novel methods for quantifying the micronutrient queuosine. Food systems and sustainability studies (Nugent, McCarthy, Woodside), funded via the UK/Irish governments (€1.2M), use a range of research methodologies to determine whether sustainable diets can support nutritional requirements and health outcomes. Our expertise in nutritional epidemiology is underpinned by molecular nutrition, for example, a deeper understanding of the importance of metabolism and the gut microbiome is being realised through sustained funding from USDA to Cassidy with Huttenhower and Rimm (Harvard). These data are being followed-up in other international cohorts, including TwinsUK, EU cohorts, including German and Danish-based cohorts, and other US cohorts including Framingham. One of our ECR's (McEvoy) recent high-profile paper in Neurology provided the evidence-base for the importance of heart-healthy diets to preserve cognitive function at midlife. Ongoing funded international projects will further explore connections between dietary patterns, brain health and cognitive ageing using population-based and RCT approaches (USDA, US AFAR, EU JPI). Our European nutritional epidemiology connections were always strong (e.g. Woodside EU H2020) exploring the health effects of iodine deficiency (EUThyroid; €3M); but are recently enhanced by the appointment of

Kuhn from the University of Heidelberg, who has extensive pan-EU collaborations, including EPIC where he was Co-PI of the Heidelberg cohort.

Spanning two Schools gives this theme important links to healthcare and drives impact. Direct links with healthcare providers are already exploited by McEvoy, McGowan and McKinley via two INTERREG European Funded Cross-border Healthcare Intervention Trials in Ireland Network (CHITIN); one exploring a multicomponent intervention for healthy neurocognitive ageing in patients with type 2 diabetes (£0.62M), which has been adopted by the world-wide FINGER network, supported by Alzheimer's Association, and the second testing a weight management intervention during pregnancy (£0.56M; both EU INTERREG VA; Special EU Programmes Body; 2019-22). QUB is leading in data linkage between existing cohort studies and government administrative (education, census, health and social care) data, with a range of Big Data infrastructure projects, and leadership of the ESRC's NI Administrative Data Research Centre and co-leadership of the Health Data Research Innovation Gateway (HDRUK) Public Health theme. Health and Social Care in NI, unlike anywhere else in the UK, are provided as an integrated service, with data held under a unique patient identifier. Such leadership is accompanied by the development of new cohort studies with data linkage already embedded, such as the NI Cohort for the Longitudinal Study of Ageing (NICOLA), where Woodside and Young lead on the dietary intake and biomarker analyses. NICOLA is now part of an international network of ageing studies, including via Dementia Platform UK.

Agriculture and Environmental Resilience
This theme focusses on animal health, welfare, production and environmental impact e.g. greenhouse gas emissions (GHG) from livestock, coupled with monitoring agricultural or climate change influences on ecosystem resilience e.g. changes in biodiversity, and environment contribution to ecosystem services. The theme consists of 31.3 FTE academic staff (3 ECRs), 20.4 PDRFs and 81 PhD students. Whilst aspects of this theme were well established prior to this REF cycle, there has since been significant growth (16 new staff joined in this cycle; Atkinson, Capellini, Chin, Creevey, Day, Geary, Gobert, Huws, Jennings, Leavitt, McMullan, McVeigh, Morgan, Pincheira-Donoso, Scollan, Theodoridou), bringing enhanced capacity in animal and environmental microbiomes, animal nutrition/health/behaviour/welfare and global change biology. The theme spans from fundamental to applied sciences, the latter enhanced by the strong collaboration with AFBI, under the QUB-AFBI alliance.

Our critical mass and disciplinary breadth enables strong interdisciplinarity and responsiveness to key priorities such as the UN sustainability goals (climate action, life above land, life below water, partnerships to achieve goals) and many UKRI priorities. For example, the theme is well-placed to help deliver on the impending deadlines to deliver on carbon neutrality by 2050, as agreed by the UK government via the Paris agreement through disciplinary excellence in animal science, parasitology, microbiology and ecology. In light of these goals and expertise, theme members have secured over £11M from H2020 and BBSRC, spanning development of new tools to discover and validate next generation drug targets in both nematode and flatworm parasites (BBSRC x4; NC3Rs x1; Maule, Marks, Mousley, Day); new on-farm management approaches to parasitism and to understand the impact of climate change on disease epidemiology (Morgan; BBSRC x2; BBSRC-GCRF x1; EU H2020 x1) and understanding in parasite-host interactions (Geary; Robinson: BBSRC x2; Kyriazakis: EU H2020 x2). We have also secured funding to develop novel methane mitigation strategies in ruminants at key life stages, coupled with understanding the fundamental mechanisms of action of these technologies on the gastrointestinal tract microbiome (Huws; Creevey: H2020 x2). Of major global significance, Allan developed the porcine circovirus 2 vaccine, the only vaccine available to treat porcine wasting disease, resulting in worldwide use and vaccine sales of £2.3 billion between 2013 and 2017 (a further impact case). This vaccine has had a global impact on pig health and productivity, whilst reducing GHG emissions and pig-gastrointestinal tract derived antimicrobial resistance.

A further £0.5M was obtained from NERC for research-spanning ecosystem services (Emmerson) and land use and climate change (Caruso), enhancing our research portfolio within

the global chain biology area. The theme, together with the School of Natural and Built Environment, also houses the UKRI-NERC DTP "QUADRAT" (£2.6M, 2019-2027) (see section 2e). More recently academic staff (McGrath) have also obtained £0.4M (SFI and industry) to respond to the global COVID-19 pandemic through the establishment an all-island SARS-CoV-2 wastewater surveillance network. Theme members have strong collaborations within the EU and international partners, based on funded projects and co-authored publications, including WUR, Universidade de Viçosa Brazil and UC Davis USA.

Enabling Technologies, Data and Data Innovation

Theme members bring leading expertise in nucleic acid, protein and metabolome-based metaomic technologies, alongside artificial intelligence, machine learning and precision sensor technologies. This is a recently established and growing theme, with substantial investment in people and infrastructure, including £1.5M investment in proteomics (see section 3c) and incorporation of 16.5 FTE academic staff (2 ECRs), 21 PDRFs, 34 PhD students into this theme. This theme is integral to IGFS, connecting to the other three research themes and being the main vehicle for connections across Faculties/GRIs (Figure 2). Members also have close interactions with ECIT and the planned GII. Close synergy with the QUB Genomics Core Technology Units (see section 3b) also aid infrastructural capacity in nucleic acid sequencing.

The expertise within this theme has already resulted in £2M H2020 and BBSRC funding (Collins, Graham, Meharg, Prodhl) to develop metabolomic technologies to study marine ecosystems through to human health. InvestNI funding was secured to use (meta)genomic and (meta)proteomic technologies, coupled with computational tools to prospect microbes for novel bioactives, alongside their characterisation and commercialisation (Allen, with Almac; £2M). More recently, funding to further enhance strengths in health informatics and artificial intelligence/machine learning was also obtained (EPSRC GCRF, £0.4M; Hardiman). Theme members also have strong connections with industry in the areas of proteomics and metabolomics (Collins, Graham, Elliott), e.g. with Agilent, AB SciEx, Bruker and Waters, resulting in significant investment in equipment (see section 3c).

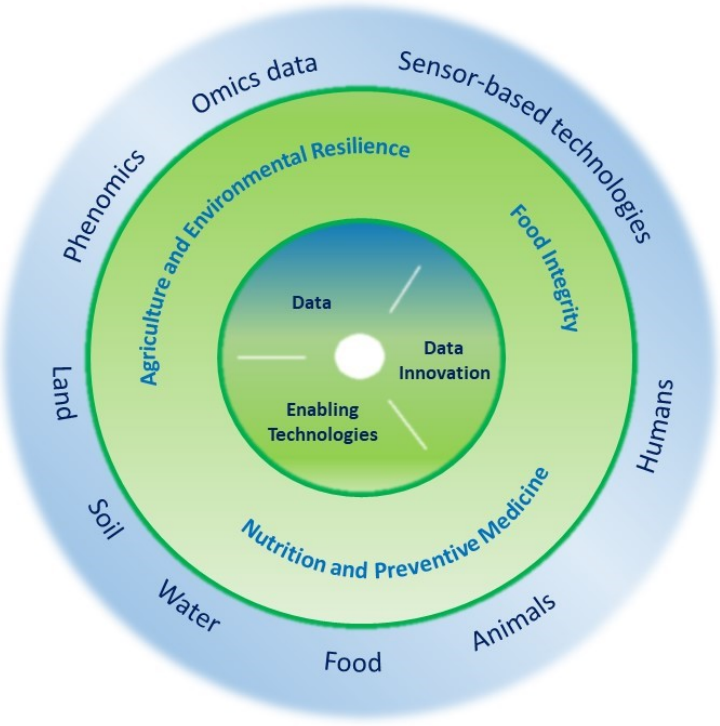

Figure 2. Enabling technologies, data and data innovation and link to other research themes

This infrastructure has led to innovations in spectrometric fingerprinting and ambient mass spectrometry which has been applied for real-time identification of non-conformities in feed and food materials (Elliott, Takats – linked to the food integrity theme), allowing for more comprehensive and cost-effective monitoring of complex supply chains. More recently our proteomic infrastructure and expertise have been used to support a multi-billion government initiative (Moonshot) to aid diagnosis of COVID-19 infections and to develop drugs for the treatment of the disease (£100K allocated to IGFS). Theme members have strong collaborations within the EU and international partners based on funded projects mentioned and/or co-authored publications, including WUR, ETH Zurich Switzerland, Max-Plank Institute Germany, California Institute of Technology USA.

d. Interdisciplinary Research (IDR)

IGFS's challenge-led themes allow interaction between researchers from a range of disciplines to address these challenges, and close links with stakeholders maximises the likely impact and relevance of the research, via the unique research-business-policy ecosystem. To encourage further interactions across the themes IGFS will:

- Ensure staff are at the forefront of their research discipline, integrating an IDR agenda, are outward facing and collaborating with world-leaders to deliver high quality IDR research.
- Develop ECR researchers and identify ambitious ECRs to co-lead the themes with a senior member of academic staff as mentor and lead.
- Support professional development/training of our research staff and PhD students in IDR research, further integrate into an IDR culture and equip them for an IDR career.
- Build critical mass and focus investment in our areas of strength and collaborate externally with world leaders in areas that are critical for leading IDR.
- Ensure our research strategy can respond to environmental, social and economic change.
- Extend global recognition and reach by further collaborating with world-leading institutes, industry, government and NGOs e.g. by capitalising on our position as UN IAEA designated centre on food and feed safety and authenticity (see section 3b) and further drive societal impact locally and globally, including within low and middle income countries.

e. Open Research

IGFS strongly and actively support the principles of open science, supported by dedicated support staff. Over the last REF cycle, open access has been embedded as the norm across QUB, and staff have access to supporting online training (see s2f). Uploading of publications to PURE, to ensure compliance for REF, has been exemplary, with IGFS staff achieving 97% compliance. We also receive significant central support from the University to help researchers in managing and sharing their datasets, including via a dedicated website, training and an institutional data repository. Specifically, IGFS staff are also able to obtain central University funding to publish in open science journals and QUB have deals with many publishers, ensuring that publication fees are not a barrier to open access. Our research Data Management Policy also aligns closely to the UK concordat on Open Research Data and IGFS staff ensure that their research is findable, accessible, re-useable and interoperable (FAIR), ensuring that other researchers can engage and benefit from the research and accelerate knowledge discoveries to benefit both society and economy. We also subscribe to ensuring that all stakeholders are aware of ongoing research and funders are notified on progress, e.g. via annual Researchfish updates.

f. Research Integrity and ethics

Research Integrity: The University supports the Universities UK (UUK) Concordat to Support Research Integrity and all IGFS staff comply with this recognised code of conduct (see s2f). For example, IGFS staff are encouraged to conduct their research in an open-manner to foster collaboration and ensure the highest level of integrity e.g. through provision of seminars, webinars and/or taking part in 'sandpit' research scoping activity. All staff have been assigned a mentor (if an ECR) or a Personal Development Reviewer, who also play a critical role in

ensuring maintenance of the highest standard of research integrity within IGFS. Any breach in expected conduct is dealt with by the QUB PVC-R.

Research Governance and Ethics**:** QUB Research and Enterprise Directorate manages research governance and ethics and advises academics on governance issues (see s2f). The directorate have implemented regulations, policies and procedures that must be complied with for research involving humans and/or animals. IGFS takes a proactive approach to ensuring compliance with legislation and institutional policies. All research undergoes scrutiny by the Faculty-based ethics committee, the Office for Research Ethics Committees in Northern Ireland (for health service-based research) or the Animals (Scientific Procedures) Act 1986 committee (for non-human animal-related research). All research projects must be logged in an online University database, for the purposes of insurance and monitoring ethical or governance issues that they raise. Staff must indicate any ethical requirements in the online portal and in addition, sign off on any grant application is conditional on the HoS being satisfied that the research can be conducted ethically. IGFS staff are also encouraged to avail of internal grant peer review procedures which aid both research excellence and compliance to integrity and ethical codes of conduct.

IGFS have a team of staff who aid researchers in ensuring all research is conducted safely and ethically, e.g. a Health and Safety Co-ordinator, COSHH Adviser, Radiation Protection Adviser, Biohazards/GMO Safety Adviser, Environmental/Fieldwork Adviser, Human Tissue Act Adviser. In addition, our staff are active members of the University Biological Safety Committee (Grant & Stewart), the Health and Safety Compliance group (Prodhl), Faculty Ethics committee (Chaired by McKinley and attended by Arnott). Staff requiring the use of the Biological Safety Unit's animal house (a QUB Core Technology Unit) are subject to the standard operating procedures and ethics governance of the facility. It is important to note that these members of staff, alongside central university Estates and Health and Safety staff, ensure that health and safety procedures are developed and complied with in light of recent COVID-19 challenges. This dedication resulted in the safe re-opening of laboratories in early July 2020, minimising COVID-19 impact, albeit at much reduced capacity.

2. People

a. Overview

Our stated strategy at REF2014 was to grow IGFS from 33.4 to 45 FTEs. We have exceeded this ambitious target, creating a thriving community of 72.8 FTEs (a 2.2-fold increase), building our critical mass across four IDR themes. To further maximise interdisciplinarity and strengthen links with world leading research institutes and major government and industry research facilities, we have invested in cross-school appointments (Cassidy), appointed staff in other Schools (McEvoy, McGowan), jointly with other Universities (Bourke, Roche, Fanning (University College Dublin), Leavitt (University of Regina), Day (Iowa State University), Geary (McGill University), Takats (Imperial College London), Vanhaecke (Ghent University), van Ruth (WUR) and Kyriazakis as a joint appointment with AFBI. These research leader appointments have been complemented by investment in research and support staff to enhance our research, education, enterprise and public engagement agenda (see below).

b. Staffing profile and recruitment

Academic Staff: The more than doubling of our academic staff over the REF cycle has ensured longer-term stability, adaptability and effective succession planning. Our thriving community now includes 72.8 FTEs (36 Professors, 24 Senior Lecturers/Readers, 20 Lecturers (50% are ECRs; Atkinson, Cameron, Chin, Kuhn, Kumaresan, Megaw, McEvoy, McGowan, McVeigh, McCarthy) (Table 1).

Table 1. Profile of IGFS staff and current PhD students by theme

	Academic staff (FTE)	ECRs	PDRFs	PhD students
Food Integrity	10.7	1	21.2	28
Nutrition & Preventive Medicine	14.3	4	27	36
Agriculture & Environmental Resilience	31.3	3	20.4	81
Enabling Technologies, Data & Data Innovation	16.5	2	21	34
Total	72.8	10	89.6	179

A central tenet of the Institute's strategic direction has been to enhance excellence and strengthen research leadership (through new senior appointments) to complement existing expertise and build core activities targeted for development, exemplified by the appointment of Collins, Graham, Hardiman to lead on a new cross cutting 'Enabling Technologies, Data and Data Innovation' theme, supported by 2 new ECR appointments and linked into the new GII (see section 3b) and Cassidy as Director for IDR and Chair in Nutrition & Preventive Medicine. Nutrition research is now an integral component within IGFS, expanding from 6 to 14.3 FTE academic staff (4 ECRs) within the last two years. Similarly, we have grown capacity in the Agricultural and Environmental Resilience theme, expanding from 10 to 31.3 FTEs (3 ECRs), within the last three years. New academic appointments across IGFS have helped maintain a balanced staff portfolio that includes ECRs to ensure appropriate succession planning, but also make new appointments in high priority areas. Over the next REF cycle we aim to build further capacity (to 90 FTEs) in the area of climate action, agricultural microbiomes and digital agriculture, plant-based diets and cardiometabolic health, food integrity, all of strategic importance to UKRI, other national/international government agencies, multinational industry and aligned to UN sustainable development goals.

Appointments to enhance engagement, impact and innovation: To complement this growth in academic staff and to accelerate engagement with stakeholders and further build our impact agenda we have secured investment from sources including the Royal Society and EU to recruit senior staff to key strategic roles, supporting our research strategy. To guide our strategic development we have set-up an ISAB board, made up of world leaders across the food security research agenda and an IAB populated by leaders in commerce and policy development.

Examples of specific roles created:

- *Director of Innovation*
  Appointed in 2016 to lead the £6.7M Agri-Food Quest Competence Centre (AFQCC), Stephane Durand has driven our enterprise interface regionally via AFQCC and internationally through EIT-Food (see section 3a). Five further professional support staff are employed to leverage industry opportunities, maintain communications with key partners and optimise EIT-Food/AFQCC networks to provide internships and placements for PhD students and PDRFs.

- *Business Alliance Manager (see s2d, s4b)*
  Dr Ann McMahon provides dedicated support for IGFS business alliance, integrated within the QUB Research and Enterprise directorate.

- *Director of Strategic Alliances*
  Appointed 2017, Paul Brereton, Professor of Practice works at the science-policy interface in UK, Ireland and Europe and is specifically focussed on building large EU-wide networks in Food Integrity.

- *Royal Society Entrepreneur in Residence*
  In 2020 Dr Jean Kennedy joined IGFS as 'Royal Society Entrepreneur in Residence' to further foster an entrepreneurial culture, accelerate translation of engagement and commercial success with industry and enhance our knowledge of cutting-edge industrial science, research and innovation.

c. Staff development and career progression

Our staff development strategy is to create interdisciplinary food system research leaders who are productive, well-networked and entrepreneurial-thinking, producing cutting-edge impactful knowledge and research to drive and actively transform food systems; skills that have been prioritised by UKRI, GCRF/Newton, DAERA, DEFRA and industry, and aligned to UN Sustainable Development goals. Our IDR themes are led by professorial researchers and co-led by ECRs to encourage involvement of junior colleagues in strategy and decision-making processes, supporting succession planning. Staff engagement in IGFS activities is facilitated through monthly theme meetings and quarterly IGFS board meetings to ensure all research staff are involved, informed and play a key role in shaping future strategic direction. All staff have the opportunity to join committees responsible for fundraising, health and safety, infrastructure, management, research strategy, PG training/progression and Athena SWAN.

Until 2019 QUB employed an annual appraisal scheme but, from 2019, in response to staff feedback, this was replaced with a new Personal Development Review (PDR), which focuses on positive development of staff on a continual basis rather than annual (see s3a). PDR is a one-to-one programme which is complemented by existing QUB-wide mentoring schemes (e.g. Queen's Gender Initiative scheme) and teams all academic staff with a reviewer from outside their direct line management structure to provide continuous support, facilitate career development and ensure all employees have the opportunity for regular, meaningful, constructive conversations. Central to the process is the generation of agreed development plans that are closely mapped against academic grade profiles to encourage progression towards promotion.

IGFS values equality and diversity and has a culture that embraces the Concordat to support career development of researchers, including as co-leads of research themes. QUB is one of only nine Silver Institutional SWAN award holders, and both SBS and SMDBS hold SWAN Athena Gold (2020). Uniquely, SBS have now achieved Gold on 3 occasions – initial award (2013) and 2 renewals (2016 and 2020).

Training in research leadership, management and entrepreneurial thinking is key to create global leaders in food systems. A variety of leadership programmes, suitable for different categories of IGFS staff and students are offered, e.g. by the William J Clinton Leadership Institute and Graduate School and the external Aurora leadership development programme for women and the European Nutrition Leadership programme at early and advanced levels. This is complemented by extensive specialist and transferable skills training and visible People and Culture teams in each School to support all IGFS staff. University policies are family friendly (e.g. flexible working, maternity/paternity/adoption/carers leave). In IGFS, 5 staff work part-time, exemplifying our support for flexible working.

New Staff Appointments: Mentors ensure new appointees experience a friendly and supportive environment that helps guide them towards confirmation in post. All new lecturer-level staff benefit from the provision of essential research/office facilities, start-up funding (appropriate to grade), a three-year restriction on teaching load and a fully-funded PhD studentship. Collaboration with established staff is encouraged. New staff can avail of support targeted at the development of international linkages through funding schemes that support international research visits and seed new projects. These include GCRF awards from the Department for the Economy (DfE) and the joint QUB-FAPESP São Paulo Researchers in International Collaboration (SPRINT) initiative which instigate pilot projects and staff exchanges.

Career Progression: During this REF cycle 26 staff (46% female and 54% male) were promoted to Senior Lecturer or Reader and 11 staff were promoted to Professor (73% female and 27% male).

d. ECRs and post-doctoral fellows (PDRFs)

Fifty per cent of our staff at Lecturer level are ECRs and 89.6 PDRFs are currently employed in IGFS (Table 1). We support these colleagues to develop their skills and training to achieve scientific independence, produce high quality research that has potential for impact and build sustainable partnerships with supervisors, mentors and world leaders in their research area. In 2018, the Faculty of Medicine, Health and Life Sciences launched a Post-Doctoral Development Centre, in which IGFS fully participates. This centre offers bespoke support and training to our PDRFs including (1) Welcoming new PDRFs and facilitating the transition from being a PGR, (2) Supporting the work of PDRFs, (3) Facilitating the career development of PDRFs, in academia and beyond, (4) Communicating career development and training opportunities, (5) Promoting industry and public engagement, (6) Influencing relevant University policies and (6) Promoting the recognition of PDRFs. This is complemented by the newly established university-wide QUB Fellowship Academy in 2020 which provides bespoke professional and career development to nurture PDRFs with outstanding potential (see s3b).

We mentor scientists applying to research fellowship schemes or grant-supported post-doctoral posts, advancing careers by providing tailored support for preparing for fellowships (exemplified by review boards for MRC Future Leaders, GCRF and BBSRC Discovery Fellowships, mentoring by past awardees). In this REF cycle, 12 young scientists in UoA6 have been awarded fellowships: 6x Marie Curie fellowships, 2x Leverhulme Early Career Fellowships, 1x Illuminate/Vice chancellor fellowship, 1x EPSRC DEFRA Fellow, 1x Royal Society Newton Fellowship and 1x MRC Early Career Research Fellow. Our ECRs have the opportunity to participate in the QUB Excellence in Leadership and Management Development Programme to strengthen and build their research leadership skills and to join the vibrant Postdoc Society within IGFS which has representation on management committees and co-ordinates the IGFS seminar programme. Other key leadership opportunities include ECRs as co-leaders of each of our 4 IDR themes.

Since REF2014**,** on an annual basis, an average of 65 research fellows have been employed in IGFS, funded from a range of sources including UKRI, EU and industry (and from diverse countries including UK, EU, Africa Brazil, China). Seven of our PDRFs have progressed to lectureships in this REF cycle.

e. **PGR Students**

Concomitant with the growth of IGFS has been a rapidly expanding doctoral student research community. In this REF cycle, 248 students completed their doctoral training and currently 179 PhD students are being trained (Table 1). Since 2014 we have far exceeded our strategic goal of doubling postgraduate student numbers. The international reach of our programmes is evidenced by ~20% of the PhD students graduated coming from outside the UK and ~7% being non-EU international students. Further growth in graduate student numbers will predominantly come from our DTPs (see below) and ongoing exchange programmes with China, Brazil, India, Malaysia and Thailand, including the Universidade de Viçosa, Minas Gerais, Brazil and Nanjing Agricultural University, China.

Training in IDR, research leadership and entrepreneurial thinking is key to creating a new generation of global leaders in food systems. Since 2014, IGFS has attracted funding for two cohort-based DTPs, nationally and internationally, including the UKRI-NERC DTP “QUADRAT” (£2.6M, 2019-27), co-hosted with the School of the Natural and Built Environment) and the UKRI-BBSRC DTP “FoodBioSystems”(£2.0M, 2020-28). For example, QUADRAT, is a substantial programme of multidisciplinary training for 100 doctoral students built around translating cutting-edge research into policy and practice for the effective stewardship of natural

capital and resource management. It also involves 34 partner and sponsor organisations, including Syngenta, Agriculture and Horticulture Development Board and Centre for Ecology and Hydrology.

This sustainable support for research training is further enhanced by on average 20 x 3-year doctoral studentships per annum from the NI DfE and DAERA (latter through competitive-bid). The Institute also currently hosts two Marie Curie Industrial Training Networks (PhoneSmartPhone, 2017-21; PROTECTED, 2017-20) and has recently been awarded a third (MONPLAS, 2020-23), with 12 PGR students each and £5.6M over 2014-2020. Other funded PhD studentships include from the Irish Agriculture and Food Development Authority (1-2 per annum) and a range of charitable and industrial sources (examples include case awards with Morrison's on environmental impact of livestock and Waters to further develop REIMS technology for food authenticity). There are currently two fellows within IGFS under the SPARK programme, a H2020-funded Marie Skłodowska-Curie DTP, while another has just been offered a position under the newly funded CITI-GENS (Collaboration in Training and Innovation for Growing, Evolving and Networked Societies), a further Marie Skłodowska-Curie DTP).

As outlined in our Institutional Statement (s3c) QUB invested £7M in a dedicated social and academic space for its postgraduate students in 2015 as a vibrant centre for academic exchange across science, arts and humanities. The Graduate School ensures IGFS post-graduate students have access to world-class facilities, Researcher Plus recognition and skills training, including in innovation and strategic leadership/management. QUB has also recently rolled out a tailored Postgraduate Career Development Programme which offers training in key areas, including Employability, Enterprise and Innovation, Personal and Professional Skills Development and Research Skills as part of their annual 10 days of training. In addition to routine, informal supervisor-student interactions, PhDs complete 10 formal supervisory meetings each year and give a presentation at the annual IGFS Postgraduate Research Symposium. Whilst PGs attend the regular seminars given by visiting research leaders and IGFS academics, the mix of student presentations and social events within the symposium week have enhanced the sense of identity and PGR integration into IGFS. PhD students are encouraged to apply for external training opportunities, with a number successfully participating in schemes such as the Parliamentary Office for Science and Technology (POST) fellowship.

Integrated Research Student Culture: The Postgraduate Research Committee oversees the development of PG research programmes and monitors all formal PG progression elements. All students have a minimum of two supervisors and, if one is on probation, the other must be a senior academic. Students are also allocated an assessor who serves as a person who monitors their progress throughout their time in IGFS but also acts as a further mentor. Our rigorous monitoring and reporting regime requires each student to complete an Initial Review at three months, Differentiation at 6-9 months and annual reports at the end of each academic year. Individual Review Panels at each stage provide specific, independent advice and help identify any potential performance issues. Where problems are identified, intermediary targets are agreed with student and supervisors to facilitate progression.

f. **Equality and diversity** (see s3d)

Our dedication to equality and diversity is exemplified by our two Athena SWAN Gold awards, and Silver Institutional SWAN award. We adopt all the QUB equality policies and, specifically, the gender actions outlined in Athena Swan commitments including: (i) providing Unconscious Bias Training; (ii) monitoring gender ratios for academic progression; and (iii) conducting exit surveys of programme graduates to establish career intentions. Our commitment to increase the diversity of our student population is exemplified by our current cohort of students from over 50 different countries.

We monitor gender statistics at all levels, from work experience placements to professorial advancement and implement practical measures such as research-only periods for academics returning from maternity leave. Our 2016 action plan addressed several gender parity

bottlenecks in the academic pipeline and implemented key actions to improve gender balance; 42% of IGFS academic staff and 54% of research staff are female. Our MB is 50% female. Of the 39.4 FTE additional academics in this REF2021 submission, 23 are female. IGFS prides itself on its collegial and inclusive culture which goes beyond the policies and services provided by the University. Three IGFS academics are SWAN champions, leading the Athena SWAN applications for their respective Schools. We lead on some key equality and diversity issues exemplified by McKinley heading the Gender Equality Office and Woodside as academic lead for mentoring within SMDBS. In terms of promotion, the 6-year average success rate for females and males is 72 and 64%, respectively.

IGFS engages closely with PRISM (the QUB LGBT staff network) and iRise (the university's Black, Asian, Minority, Ethnic (BAME) and International Staff Network), celebrating the diversity of our staff and promoting the Institute and University as a welcoming place to work. Dean currently leads a BAME taskforce initiative for the University on behalf of the Vice-Chancellor.

3. Income, infrastructure and facilities

a. Overview of research grants/income and strategies for funding

Since 2014, our research income has increased 3-fold to £59.1M and become more diverse (14.9% UKRI, 37.1% EU and 5.8% from non-EU sources (predominantly US government, Gates Foundation)).

Our ongoing strategy to sustain and increase research income has 5 elements:

a. Further increase success rates by continuing mandatory internal and Faculty peer review of UKRI grant applications from ECRs and probationary staff (including grant-building sandpits).
b. Capitalise on support for strategic partnerships, DTPs (e.g. include guaranteed PhD studentships for all awards >£500k, matched studentships/support staff costs for DTPs), sabbaticals/secondments to better position us for IDR global initiatives.
c. Ensure mentorship of staff through our PDR programme (personal development, enhancing grantsmanship, instilling importance of networking with world leaders)
d. Further build 'team science' through our IDR themes so we are optimally positioned to influence and respond to large national/global initiatives.
e. Further build and strengthen our enterprise/industry ecosystem internationally (e.g. through EIT-Food (see below).

A major focus is on translation and commercialisation of research, ensuring we are closely aligned and able to influence and respond to UKRI and H2020 initiatives. For example, IGFS is the base for Agri-Food QUEST, a membership-based, industry-led Innovation Centre for the agri-food businesses in NI (£6.7M, 2015-20) focused on supporting the NI Agri-Food Strategy Board "Going For Growth" strategy which aims to grow the agri-business sector by 60% to £7bn. This investment positioned us for a leading strategic role in EIT-Food. To date IGFS has received €5M (2018-2020); one of the top three beneficiaries of EIT Food investment, but EIT-Food also provides opportunities for research internships, and technical/business focused training. To enhance research translation, we have established sustainable research partnerships with major industries, e.g. multiple joint UK/EU government/industrial funding awards (13 KTP/RCUK-LINK/InvestNI co-funded industrial partnership awards over this REF cycle). We have also had significant success with KTP projects, including recent awards to: 1) reduce the impact of intensive animal farming on climate change/land use; and 2) address micronutrient deficiencies associated with plant-based diets.

Examples of success by themes include:

Food integrity: Significant EU funding in food safety research awarded, including €10M through joint funding from H2020 and the Chinese Ministry of Science and Technology (MOST) for IGFS-

led research on food authenticity. Recent awards include The MONPLAS ITN project (€6M, 2020-23) to develop robust, easy to use and inexpensive technologies to perform in situ detection of micro and nano-plastic contaminants within the environment, GCRF funding (£0.5M, 2019-22) on agronomic sustainability has combined state-of-the-art analytical and molecular approaches to interrogate soil-plant biogeochemical cycles and develop food safety interventions in developing countries with a focus on toxins in rice in Bangladesh and China.

Nutrition & Preventive Medicine: Recent awards include €1.2M (2020-24) to determine whether sustainable diets can support nutritional requirements, $1.5M (2020-23) from US Dept of Agriculture to conduct complex interventions and population-based studies on plant-based diet and cardiometabolic health, £3.25M (2019-24) from the US-Ireland R&D Partnership Programme (NIH/HRB/SFI/NI R&D Office/MRC) to develop a panel of dietary biomarkers, £2.5M (2019-24) from US-Ireland R&D Partnership Programme to develop novel methods for quantifying the micronutrient queuosine and $1.75M (2020-23) from the US National Institutes of Ageing on dementia biomarkers.

Agriculture and Environmental Resilience: Since 2017, with the appointments of Huws and Creevey, a platform for microbiome research in relation to agriculture and climate change has been developed, leveraging €2M H2020, a series of EU JPIs (€1.5M) and strategic links to the Global Research Alliance in Agriculture and Greenhouse Gases (GRA). In animal health, recent awards include 7 awards from UKRI (e.g. 9 BBSRC awards, £5M, one a BBSRC-Link with Boeringer-Manheim; £1.2M) and 3 x H2020 (€3M), to study livestock health and parasite function.

Enabling Technologies, Data and Data Innovation: Examples of recent awards include £2M from H2020 and BBSRC funding to develop metaomic technologies to study marine ecosystems through to human health. InvestNI and Almac industrial funding (£2M) was also secured to use (meta)genomic and (meta)proteomic technologies, coupled with computational tools to prospect microbes for novel bioactives, alongside their characterisation and commercial development.

Early Career Researcher success: The success of our ECRs is evidenced by recent success of 3 ECRs:

Atkinson - £1.2M BBSRC (Co-I, 2019-22), £100k Academy of Medical Sciences (PI, 2018-21)
McEvoy - €0.68M EU JPI (PI, 2021-24)
Cameron - £0.11M BBSRC (PI, 2020-24)

b. **Organisational infrastructure and support for research and impact**

During this REF Cycle, the foundation of IGFS as a GRI in 2016 has led to unprecedented physical development to drive our position as a global leader in food security.

Investments and plans to sustain growth: The current REF cycle has included continued support for IGFS: started in 2013, an international fundraising campaign (designated *Beyond*) by the QUB Foundation in support of transformational projects (including £10M towards the new IGFS building) reached its target of £140M one year ahead of schedule. The design of the IGFS £39M building, the move to have all IGFS staff under one roof and the shared laboratory environment maximises interactions and reinforces the drive towards more IDR research. Looking forward, a series of high-level engagements with major industries/leading companies are underway with a view to additional infrastructure investments to extend the new building.

Global Innovation Institute (GII)
As an integral partner in the GII (see s4C) this initiative will provide major technological advances, give rise to enhanced expertise in digital technology affording new opportunities for IGFS to harness the potential of emerging technologies in agri-food, nutrition and healthcare to enable a transformational One Health approach.

ASSET Lab
The ASSET Technology Centre became the world's first accredited laboratory for the detection of herb and spice adulteration using a non-targeted molecular spectroscopy method (UKAS ISO 17025), leading, in 2019, to an ISO accreditation for authenticity testing of herbs and spices, a particularly rare achievement. Recently, the UN IAEA designated IGFS as an IAEA Collaborating Centre recognising its global reach in food safety, authenticity and traceability. IGFS is also a 'Food Authenticity Centre of Expertise' following acknowledgement of its proficiency in July 2020 by DEFRA, the UK FSA and Food Safety Scotland; QUB is the only University to hold this status.

Core Technology Units
QUB houses 4 Core Technology Units: Genomics, Advanced Informatics, Biological Services and Advanced Imaging. These facilities are available to all staff, operating at low-cost and are complimented by the recent investment in high performance computational infrastructure (£6M), which recently obtained Tier 2 status, resulting in QUB being one of the few universities globally with this level of capability.

Clinical trial facilities
Our existing clinical trial facilities are state-of-the-art but, through Belfast City Deal investment (innovation strand, iREACH), a further £10M will be invested over the next REF cycle to further enhance our clinical research capabilities.

Targeted Internal Initiatives:

- *ESRC Impact accelerator fund*
  £1M to tackle major societal challenges globally, examples include overcoming the challenges of the global ban on Zinc oxide in pig feed supplementation by 2022, and formulating novel treatments for Blackhead disease in poultry.
- *Global Challenge networking programme*
  GCRF funding provided by DfE supports up to £25k for pump-priming activities (including workshops/pilot projects). Recent examples include funding to build a network on climate change in Brazil, and parasitology projects in Azerbaijan.
- *Illuminate Vice-Chancellor Fellowship Scheme*
  A 5 year position with an academic career path. IGFS was awarded one of three (Cameron).
- *DfE and DAERA studentships* -18-22 studentships per year were allocated to IGFS over the current REF period. In addition we compete for additional CASE DfE studentships annually, winning 3-4 per annum.
- *Engaged Research Seed Fund*
  Recent examples include funding to install an on-street audio installation (Poetry Jukebox, 2021) an innovative way to integrate arts and science, using poetry to showcase the complexities of food systems and the debates needed to shape the future of food systems.
- *IGFS travel and pilot grant fund*
  Providing funding, mainly targeted at ECRs, to travel and spend time in world leading laboratories, networking opportunities through a competitive 'Internationalisation Funding Scheme'.

Support for research and impact: Our 60-strong central Research and Enterprise Directorate provides support for research, commercialisation, ethics and governance (see s4b). IGFS have additional dedicated internal support (see section 2b).

c. Operational infrastructure, facilities and specialist equipment

The growth in staff numbers has been accompanied by investment in facilities, refurbishment and expansion (>£55M) exemplified by our new state-of-the-art building. Since occupying the building in April 2019 we have invested >£5 million in new technologies to ensure we are at the

cutting edge of our fields. Outlined below are the major investments in this REF cycle and our ongoing plans:

Enabling technologies and data innovation investment: There are 4 Core Technology Units (section 3b). Physical resources encompass bespoke analytical, bioanalytical, molecular biological, genomics, proteomic, cell/tissue culture and bioimaging laboratory space. The Bioimaging Core Technology Unit hosts flow cytometry, microscopy, live cell and *in vivo* imaging system facilities, high resolution slide scanning and microinjection equipment and a dedicated server for data storage and remote access. Capacity in genomics includes an ABI 3730XL 96 Capillary DNA analyser for high-throughput Sanger sequencing and microsatellite genotyping. Advanced informatics is strongly linked to the new GII. Another major addition is in high-throughput MS-based proteomics. Investment has included recruitment of senior academic staff (Readers in Proteomics (Collins, ETH Zurich and Graham, Manchester), £1.5M to acquire a suite of modern MS devices (x3 Brucker and SCIEX) and associated technical support (Research Technician/PDRF x2).

The ASSET Technology Centre (see section 3b) has had continued infrastructure development within the assessment period (£10M) to further enhance its unique, custom-built technologies that draw on inter-disciplinary skill-sets that support the development of innovative strategies and techniques in animal and human health, food safety monitoring and traceability, providing a niche food-forensic strength for IGFS. ASSET has had a long-standing relationship with Waters Corporation and addition of REIMS technology further enhances our technological capabilities. We have recently extended our relationship with Agilent, resulting in investment in additional MS capabilities (£1.5M). ASSET also houses in-kind donations of spectrometry (triple quadrupole, Q-TOF-, LC-TOF-, GC-, isotope ratio and ICP-mass spectrometry), spectroscopy (XRF, confocal Raman microspectroscopy) and biosensor equipment from a range of companies, including Waters, Agilent, Thermo-Fisher. ASSET is a sector leader in the development and exploitation of biosensor technologies for food safety and integrity.

The Centre for Plasma in Agri-Food (AgriPlas) opened June 2019, funded through the Centre for Innovation Excellence in Livestock (CIEL), with £0.4M investment from Innovate UK and builds on our existing expertise in plasma knowledge. A team of IDR scientists (physicists, pharmacists, animal-health experts, feed and food safety experts and analytical chemists) develop cold plasma technology-based solutions that lead to reduced use of chemicals and antibiotics in food-production systems, ultimately enhancing the sustainability and global marketability of the NI, UK and international agri-food industry. This facility is the first of its kind in Europe.

Animal and marine facilities: Researchers have access to state-of-the-art animal house/holding facilities. Parasite behaviour assessment to validate parasite drug and vaccine targets for industrial partners encompass purpose-built bioassay systems, motor function and muscle assay rigs and a range of computational behavioural analysis platforms that provide a unique facility dedicated to parasite functional genomics. Animal production, health and welfare researchers have a collaborative large animal base at AFBI. The pig unit includes specialised facilities for behaviour and welfare research containing open-field test arenas and electronic feeders. A dairy unit comprises a 300 high-genetic dairy herd with access to detailed animal records (genetics, health, productivity). IGFS also houses unique and rare capabilities within our marine facilities (Queen's Marine Laboratory; QML), an established aquatic mesocosm research platform with direct access to Strangford Lough, a Special Area of Conservation under the EU Habitats Directive, and Northern Ireland's first Marine Conservation Zone under the EU Marine Strategy Framework Directive.

Clinical trial facilities: Human study facilities are co-located on the same sites as our major medical specialty tertiary referral Centres (Royal Victoria Hospital and Belfast City Hospital), making them ideal for the recruitment of clinical populations, with an accompanying interview, biological sample collection and storage suite within CPH, and full clinical research capability within the Wellcome Trust-Wolfson Northern Ireland Clinical Research Facility. CPH provides

state-of-the-art statistical expertise, and methodological innovation for designing and analysing clinical trials and nutritional epidemiological research and is also the home to the Northern Ireland Clinical Trials Unit (NICTU), a UK Clinical Research Collaboration (UKCRC)-registered Clinical Trials Unit. These facilities are supported by the facilities within IGFS (ASSET) for the analysis of established and novel nutrition/health biomarkers. Such omics technologies are currently being used within a £2.5M US-Ireland award designed to develop new micronutrient-focused biomarkers. Through the Belfast City Deal investment (innovation strand, iREACH, £10M) additional clinical research infrastructure will be established.

Sustained engagement with Industry: Ongoing University support has also been secured for the development of a dedicated site adjacent to the new building for industry and other partners to 'hot-desk' and engage with IGFS researchers. Looking forward, a series of high-level engagements with major industries/leading companies are underway with a view to additional infrastructure investments.

Future plans include:

- Development of a partnership with UK National Measurement Laboratory (NML at Laboratory of Government Chemist). NML is the UK's designated institute ensuring trust and confidence in chemical and bio-measurements. The intention, which is in advanced planning stages, is to create a Centre of Excellence in Agriculture and Food Integrity delivered by IGFS as part of the NML network with an overarching aim to further promote and strengthen academic and industry links between NML, the University, and UK agri-food industries.
- Establishment of an All-Island Centre on Food Integrity (Food-I). The aim is to employ an IDR and innovation agenda focused on the island of Ireland as a model of transforming food systems towards a more environmentally and economically sustainable, transparent agri-food sector with potential funding earmarked from SFI and DfE £40m).
- Eden Project Foyle - an ambitious and potentially transformative project in terms of economic development, education, the environment and social inclusion. IGFS will be research partners providing a focus on the environment and wellbeing. Built on the experience of the Eden Project in Cornwall, through partnership with Foyle River Gardens Trust, the project will assist in the regeneration of Derry/Londonderry generating £62.3M per annum and supporting 2,233 jobs. Support comes from British/Irish governments, as described in the New Decade, New Approach Deal (January 2020).

4. Collaboration and contribution to the research base, economy and society

a. Overview

The re-modelling and growth of our core challenge-led research themes over the REF period ensures that IGFS staff are better placed to co-ordinate research and build relationships with policy makers, businesses and other key stakeholder organisations. We collaborate with world leaders in our field exemplified by long-standing collaborations with UC Davis, Harvard, WUR, Chinese Academy of Sciences and ETH Zurich and evidenced by the high levels of international co-authorship (66% - 2014-20 (Russell group average 55.1%). Our researchers have made substantial contributions to industry including (1) the development of the porcine circovirus 2 vaccine, the only vaccine available to treat porcine wasting disease (Allan), resulting in worldwide use and vaccine sales of >£2.3 billion; (2) Food Fortress©, a unique world leading risk-based supply chain management tool established in 2014 and now implemented by >70 global food/feed companies; (3) following the 2013 European Horsemeat Scandal, Elliott was commissioned by UK Government to conduct a review of the UK food supply system. The 'Elliott Review' resulted in establishment of a National and Scottish Food Crime Unit and a UK wide Food Industry Intelligence Network. Recent examples of successful engagement and impact include the implementation of hand-held sensor technologies developed and validated into on-line quality control testing of raw materials.

b. Academic collaborations and contribution to the wider academic community

Academic collaborations with world-leaders: IGFS staff have developed enduring collaborations with some of the most esteemed research institutions in the field including: the Chinese Academy of Sciences (China), Harvard TH Chan School of Public Health, Broad Institute, UC Davis and Berkeley, NASA Ames Research Center (US), McGill, Alberta (Canada), University of Stellenbosch, Free University of Berlin, Universidade de Viçosa, ETH Zurich, WUR.

Cross School/Faculty collaborations – IGFS is embedded in SBS with major links to SMDBS and more recently other Schools/Faculties/GRIs. Examples include H2020 and BBSRC projects addressing improvements in animal health, welfare and environmental impact of livestock systems through use of AI (Kyriazakis) with ECIT; InvestNI AFQCC exploring novel approaches to recovery and recycling of phosphorus from waste (McGrath) with Chemistry & Chemical Engineering; BBSRC EnvironSafe: cold plasma innovations for food safety and sustainability (Elliott) with Schools of Pharmacy, Mathematics and Physics.

National collaborations – We have participated and led numerous UKRI, Innovate UK and All Ireland SFI/DAFM/DAERA projects. Examples include parasite control (BBSRC, Maule and University of Liverpool); SFI project addressing methane abatement in ruminants (Huws/Creevey, University of Galway and Teagasc).

International collaborations – Academics have participated and led a diverse range of EU FP networks since 2014 including EU-CHINASAFE, FOODINTEGRITY, AUTHENT-NET, Vivaldi, ECO-FCE EU JPI. Recent EU networks have led to success in H2020, including MASTER (€10.9M, Creevey, Huws, 2019-23). The sustained nature of the collaborations is exemplified by visiting Professorial positions, include e.g. Elliott (Chinese Agricultural University, Beijing); Cassidy (Harvard TH Chan School of Public Health, US), Krska (Chinese Academy of Agricultural Sciences).

Examples of our thriving academic collaborations by theme include:

Food Integrity: Cao has developed extensive collaborations with leading researchers in the area of (bio)analytical sensing and diagnostic tools for food safety/quality analyses including at Nanyang Technological University of Singapore (Qihua) and Technical University of Denmark (Wolff, Bang). Recent successes include participation in the EU FoodSmartPhone and MONPLAS (led by Aston University UK) to develop on-site analytical tools for monitoring contaminants including micro and nano-plastics in water. A series of recent NERC and BBSRC Newton Foundation and GCRF awards (totalling >£3M) reflect the extensive collaboration of Meharg, Meharg & Williams with scientists at Bangladesh Agricultural University (Sumon) and at Chinese Academy of Science (Zhu). Mooney has developed an interdisciplinary collaboration with sensor specialists at the Georgia Institute of Technology (Vogel) (US) and the Tyndall National Institute (O'Riordan; Ireland) leading to a 4-year US-Ireland R&D Programme research programme (£1M, jointly funded by the US Department of Agriculture, SFI, DAERA) to develop on-farm animal disease diagnostics. Campbell's expertise on development of innovative diagnostics for a wide range of toxins has led to extensive collaborations both in EU shellfish food safety research programmes and in recent UKRI GCRF initiatives focussed on safe drinking water provision in developing countries. This includes a recent BBSRC (£1.6M) programme in conjunction with University of Sri Jayewardenepura, Sri Lanka (Manage), Aberdeen Industrial Biotechnology Institute (Edwards, Lawton) and the UK Biochar Research Centre, University of Edinburgh (Masek), to develop solutions to eliminate cyanotoxin exposure via water.

Nutrition & Preventive Medicine: Our expertise in plant-based diets and cardiometabolic health is part of a long-term collaboration with Harvard. Cassidy has collaborated with them since 2006, with 25 high-impact papers published since 2014, including in the BMJ/AJCN. Over the last REF cycle they have been awarded joint research grants >£1.6M to conduct complex interventions and population-based research on dietary flavonoids, with two recent awards from

USDA ($0.3M (Cassidy/Rimm PI) and $0.85M (Mukamal PI), 2020-23), consolidating and sustaining their collaborations on plant-based diets/flavonoids. Woodside has recently been awarded (2019-2024) a prestigious US-Ireland R&D Partnership Programme (£3M multi-agency funding including NIH/SFI/MRC) with Harvard to explore novel biomarkers. Green extends the US-linked successes, with recent awards with the University of Florida to develop novel biomarkers.

Agriculture and Environmental Resilience: Our expertise in animal science and microbiome research, parasite biology and global change biology has led to many global collaborations. For example, Huws and Creevey have collaborated with leading institutes, including AgResearch New Zealand (Attwood), INRAE France (Morgavi), WUR (Smidt), University of Alberta Canada (Guan), and Universidade de Viçosa Brazil (Mantovani), resulting in co-authored publications in Nature Microbiology/Comms, ISMEJ and Microbiome and >£3M joint funding to study livestock microbiomes in relation to host phenotype and GHG emissions, from UKRI, H2020, EU JPIs and DAFM/DAERA. Global collaborations in the field of parasite biology and effects of climate change on parasite epidemiology are also noteworthy e.g. PIs Kyriazakis, Maule, Morgan and Gobert have collaborations with Swedish University of Agricultural Sciences (Rydhmer), University of Calgary, Canada (Gilleard), Norwegian University of Life Sciences (Overland), Chinese Academy of Agricultural Sciences, China (Umbrella Organisation for several Chinese Universities), Aarhus University, Denmark (Bach-Knudsen), University of Copenhagen, Denmark (Thamsborg), University of Ghent, Belgium (Vercruysse), University of Pretoria, South Africa (Van Wyk); Lilongwe University, Malawi (Safalaoh) to name a few. These collaborations have resulted in publications in PLoS Pathogens, Genome Biology, Science Advances and Global Change Biology, underpinned by >5M funding from UKRI, EU H2020, EU ERA Net, DAFM/DAERA, Defra, GCRF and Gates Foundation.

Enabling Technologies, Data and Data Innovation: As noted previously, this is a relatively new theme founded on excellence in metaomic technologies, machine learning/artificial intelligence and digital sensor technologies with the latter two in collaboration with the GII. Theme members collaborate with globally-recognised establishments e.g. Medical University of South Carolina USA (MUSA; Hazard, Wrangle), ETH Zurich (Aebersold). These collaborations have resulted in co-authored publications in Nature Methods/Biotechnology/Medicine/Comms, Cell, and PNAS. Core staff within this theme (Collins, Graham and Hardiman) are new appointments (2018-) brought in to enhance the excellence in this area. To date the core staff have secured UKRI and H2020 funding >£2M funding, much of which is collaborative with MUSA and ETH Zurich.

c. Examples of contributions to the discipline and wider academic community

Fellowships / Awards / Honours: In 2018 and 2020 respectively, Meharg and Elliott became Elected Fellows of the Royal Irish Academy (RIA). In 2017 Elliott also obtained an OBE title and in the same year an Outstanding Achievement Award The Theophilus Redwood Award, RSC. Williams was awarded a Chinese Academy of Sciences President's International Fellowship Award (2016); Fanning elected Fellow of the American Academy of Microbiology (2019); Cassidy held a Royal Society Wolfson Research Merit Award (2013-18); Su, 2019, and Cassidy, 2017 were elected Fellows of the American Heart Association (FAHA).

Our ECRs have demonstrated their future potential and vitality, e.g. McEvoy was awarded Senior Atlantic Fellow of The Global Brain Health Institute (GBHI), University of California San Francisco (2016), and also held a Paul Beeson-CARDI Fellowship of the American Federation for Aging Research (AFAR, 2015-20), working with Woodside. Bondonno was awarded a 4-year Australian National Health and Medical Research Council (NHMRC) Early Career Fellowship to work with Cassidy (2018-22). Wu was also awarded Royal Society Newton Fellowship (2020-22) to work with Elliott.

Government Committees: Young (Chief Scientist, NI Government 2019-); Young (Member of Scientific Advisory Group on Emergencies, SAGE 2020-); Elliott (Deputy Chair, REF2021 UoA

6), Cassidy (member, REF2021 UoA 3); Elliott (Chair, Government review of integrity and assurance of UK food supply networks; 2014); Elliott (Independent Science Advisor World Food Programme 2019-); Young (Chair Joint Committee for Traceability in Laboratory Medicine 2019-21, Chair, International Federation of Clinical Chemistry Scientific Division 2015-18); Connolly (Expert member EFSA Scientific panel: Food contact materials, enzymes, processing aids); Maule (Wellcome Trust Strategic Awards Committee 2015, Swedish Research Council-Infectious Disease Committee 2014-); Mooney (BBSRC Committee A 2018-); Kyriazakis (panel member BBSRC/ESCR/MRC tackling antimicrobial action 2016 and Global Challenge Fund, 2019); Fanning (Foreign Expert for China National Centre for Food Safety & Risk Assessment [CFSA], 2015-, and Saudi Food & Drug Authority [SFDA] 2019-22); Fanning (FAO/WHO expert on food-borne antimicrobial resistance 2018-23); Fanning (UK Food Standards Agency expert working group to evaluate hydrolysed infant formulas 2015). Fanning (WHO/FAO expert panel to assess the risk to human health of PlumpyNut® to severe acutely malnourished children, UN-FAO, 2014); McGrath (member International Advisory Panel for Enterprise Ireland Dairy Processing Centre); McGrath (UK Representative on United States National Science Foundation Sustainable Phosphorus Research Coordination Network 2015-19); Roche (UK Nutrition Research Partnership Committee (Wellcome Trust/MRC) 2018-20, and Chair, Scientific Advisory Board, EU Healthy Diet Healthy Life JPI 2015-18).

Editorial Boards of National/International Journals: Huws, Cameron, Kumaresan (2015-) (Microbiome); Maule Int J Parasitology (2017-19); Geary J Parasitology (1993-) and Int J Parasitology-Drug Discovery and Resistance (2011-); Fanning (2013-) (FEMS Microbiol Lett, Microbiology). Huws editor-in-chief, Animal Microbiome (a sister journal to Microbiome) (2018-).

Selected Advisory Boards: Allan (Merial; Devenish Nutrition; FDA, USA); Connolly (Fusion Antibodies; XenoSense Ltd.); Elliott (Neogen Corp; Chief Scientific Advisor, IAEA/FAO; Agri-Food QUEST); Fanning (Director WHO *Cronobacter* Centre; MRC; UN, FAO & FSA adviser); Geary (Boehringer-Ingelheim 2019-); McGrath (Microbiology Awareness Campaign - NI Assembly & Oireachtas, RoI); Meharg (FDA; Fund for Scientific Research, Belgium;); Prodohl (ICES Working Group, Genetics in Fisheries & Mariculture; NERC Advisory Scientific Committee).

Selected Learned Society Positions: Maule (RIA Life Sciences Committee and Selection Committee 2013-15) and Swedish Research Council Infectious Diseases panel (2013-19); Meharg (Fellow, Royal Society of Edinburgh, International and Selection Committee 2012-16); Scollan (Chair Management Board Animal 2014-20); Woodside (Trustee and Honorary Publications Officer, Nutrition Society 2019-).

Selected Conferences Hosted / Organised: Scollan (Director of Oxford Farming Conference 2017-20); Maule (Organising committee Global Health Symposium, Belfast 2017, 2018); Woodside (Organising committee Federation of European Nutrition Societies, Dublin 2019). Elliott: (ASSET Summit on Global Food Integrity 2018); Kyriazakis (chairman, International Advisory Committee for International Symposium on Nutrition of Herbivores, 2014-18).

d. Engagement with non-academic communities

Our engagement with policy makers and industry has intensified since REF2014. With respect to seeding innovation and impact development, formal linkages with multiple, global stakeholders have been established through, for example, AgriFood Quest and EIT-Food, and our strategic alliance with AFBI enhances our industrial and policy impacts. We have further enhanced our engagement with government nationally (e.g. FSA, Elliott review, FINN network (food authenticity network to support evidence-based policy making) and internationally (e.g. Huws is Chair of Rumen Microbial Genomics network which underpins the activities of the GRA in GHG mitigation, and Kyriazakis's work with FAO). A series of knowledge networks have been established collaboratively between IGFS and *Safefood* on the island of Ireland that help integrate activity and provide for research synergy; the IGFS footprint in Ireland is further enhanced through the Food Fortress© concept.

Industrial research collaborations during the REF cycle involved: Pharmaceutical [Aviagen, Bayer, DOW, GlaxoSmithKlein, Merial, Zoetis, Mondelez], Diagnostic [Neogen Corp., R-Biopharm AG, Syngenta, Virbac], Biotechnology [Waters, Xenosense, Agilent, Bruker] and Food [Avondale, Agrisearch, BioAtlantis, Crossgar Meats, Dromona, Dunbia, Fleming Poultry, Moypark, Nestle, Skea Eggs, Thompson's Feeds] industries. Many of these are ongoing and expanding.

IGFS also hosts a number of keynote lectures to the non-academic community, including an annual lecture and the George Scott Robertson Lecture. We run a host of events in partnership, such as the Oxford Farming Conference and Coalition of Aid and Development Agencies (CADA) One World Festival and actively engage with the public and schools e.g. through the Northern Ireland Science Festival and within school bespoke Microbiology Society-sponsored events.

Policy engagement examples:

Professor Morgan was one of fifteen selected global experts in helminth control appointed to the Star-IDAZ International Research Consortium on Animal Health, and led on research roadmaps for integrated control of nematode and fluke infections in livestock. He has also supported UN and national governments on emergency investigation of wildlife mortality events in saiga antelopes (2015) and elephants (2020), leading to improved tools for monitoring and investigation of wildlife health.

Professor Young is the Chief Scientific Advisor to the Department of Health (2015-present) and also the Scientific Advisory Committee for Emergencies (SAGE; 2020-present). Professor Cassidy has contributed a systematic review on flavan-3-ols and cardiovascular health which is being used to develop dietary guidelines for flavonoid intakes data by the American Academy of Nutrition & Dietetics (2020-). Professor Woodside has, through the International Life Sciences Institute (ILSI), led the development of guidelines on the design, conduct and reporting of food-based intervention studies in both adults and children. Professor Elliott acted as Independent Science Advisor to the World Food Programme (2019-20) during the Uganda crisis. He also acts as an advisor to the National Food Crime Unit and sits on the CODEX Alimentarius working group on food fraud Elliott is a partner with a number of multinational food corporations on a food safety initiative which is part of the UN Food Systems Summit in September 2021.