Working Paper

Technology and climate change

A review of STFC Food Network+ projects and future potential

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Abstract

New and emerging technologies have the potential to reduce greenhouse gas (GHG) emissions from the agri-food sector. This exploratory study identified trends, opportunities and constraints in the application of emerging technologies to climate-related challenges within the agri-food system. We focused on projects supported by the Science and Technology Facilities Council (STFC) Food Network+ (SFN). The SFN provides seed funding for projects that address sustainability challenges across the food system by applying STFC technological capabilities and bringing together stakeholders from academia and industry to match practical needs with technological capabilities. SFN-funded initiatives represent a promising sample of interdisciplinary projects that bring together new and emerging technologies to address food systems challenges.

We reviewed a sample of 18 SFN-funded projects. The majority of projects reviewed (83 per cent, or 15 of 18) exhibited the potential for indirect greenhouse gas reductions, mostly through efficiency gains either at the agricultural production stage or further along the supply chain. A smaller number (17 per cent, or 3 of 18) had direct potential for greenhouse gas reduction. The technologies most commonly applied within the projects reviewed included: sensing and imaging, large-scale data science, and data sharing. Of these, three projects used a combination of these three technology types. These findings are based on a small sample of projects, but they are nevertheless indicative of emerging trends and promising avenues for further exploration, as well as potential challenges in the application of technologies developed in one sector to those experienced in another.

1. Introduction and background

New and emerging technologies have the potential to reduce greenhouse gas (GHG) emissions from the agri-food sector. We assessed this potential through an exploratory study conducted by RAND Europe with support from the Science and Technology Facilities Council (STFC) Food Network+ (SFN). The study aimed to identify trends, opportunities and constraints in the application of emerging technologies to climate-related challenges within the agri-food system in order to inform future research on the topic.

We focused specifically on SFN-supported initiatives. The SFN provides seed funding for small projects that aim to address sustainability challenges across the food system. It does so by applying the technological capabilities of the STFC – which funds the UK's fundamental research into astronomy, nuclear physics, particle physics and particle astrophysics, and hosts large-scale, specialist facilities for conducting advanced physical and life sciences research – to these issues. The SFN brings together stakeholders from across the STFC, relevant academic networks such as N8 AgriFood,[1] and industry partners, in order to match practical needs with technological capabilities. SFN-funded initiatives represent a ready and promising sample of interdisciplinary projects that bring together new and emerging technologies to address food systems challenges.

1.1. Climate change poses significant challenges to agri-food systems

Climate change has the potential to affect all aspects of food security. For example, climate change has already been linked to decreases in crop yields due to drought, flooding and changing rainfall patterns, with corresponding effects on food prices.[2] Coupled with a predicted 70 per cent growth in demand for food by 2050, the impacts of climate change clearly represent a growing risk.[3]

At the same time, activities across the agri-food system contribute to GHG emissions, with the majority occurring at the agricultural production stage.[4] In the UK alone, agriculture is estimated to be responsible for at least 10 per cent of GHG emissions.[5] Primary agricultural emissions include nitrous oxide (N_20),

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[1] The N8 AgriFood network is a grouping of eight research-intensive universities in the north of England who possess expertise in agri-food. It aims to address food-security challenges across the natural and social sciences. For more information see N8Agrifood (2019).

[2] de Coninck et al. (2018).

[3] Alexandratos & Bruinsma (2012).

[4] Garnett et al. (2016).

[5] Parliamentary Office of Science and Technology (2019).

methane gas (CH_4) and carbon dioxide (CO_2). Nitrous oxide is released by microorganisms in the soil following fertiliser application or from ammonia deposits, while methane gas is released by ruminant livestock (e.g. cows and sheep) and through the decomposition of organic matter in flooded agricultural land. Carbon dioxide enters the system through on-farm energy use and/or land-use changes (e.g. draining peatlands for conversion to agricultural use).[6] The proportion of GHG emissions related to agriculture within the UK could increase significantly due to difficulties in reducing emissions from the sector and more rapid emissions cuts in other sectors (e.g. energy).[7] Manufacturing and transport in the supply chain also contribute to GHG emissions. Consumer demand plays a significant role as a driver of agricultural production (e.g. dietary preferences for meat).

These factors together constitute the genesis of a major technical and policy challenge: the agri-food system in the UK and globally will need to produce more food while reducing GHG emissions in order to sustainably feed a growing population. Technological advances can be important enablers in reducing GHG emissions across the agri-food sector.[8]

1.2. The SFN provides an opportunity to test how emerging technologies may address climate-related agri-food challenges

The STFC possesses significant technological capabilities. These include large data-science capabilities (e.g. software and hardware to process large amounts of data from new instruments, as well as machine learning), advanced technologies (e.g. sensors, detectors and cameras as well as robust, portable analytical tools designed for small spacecraft), and the UK's biggest science facilities (probing materials from the subatomic to molecular scales using high energy synchrotron, neutrons, muons and lasers). The STFC enables these capabilities to be applied through its research in astro-, nuclear, and particle physics as well as space science, and underpins the research of the other six research councils.[9] As previously noted, the aim of the SFN is to apply these technologies to complex issues within the food system.

Figure 1 depicts how STFC capabilities in each area (data science, technology and facilities) intersect with challenges in the food system. Conceptually, the SFN divides these into three separate domains. The first is sustainable food production, which primarily focuses on agricultural production or 'pre-farmgate' activities. The second area is resilient food supply chains, which encompasses food supply networks from 'farm-to-fork', or 'post-farmgate' activities. The third area is focused on improved nutrition and consumer behaviour, including challenges such as hunger, as well as healthy and sustainable diets.[10]

[6] Parliamentary Office of Science and Technology (2019).

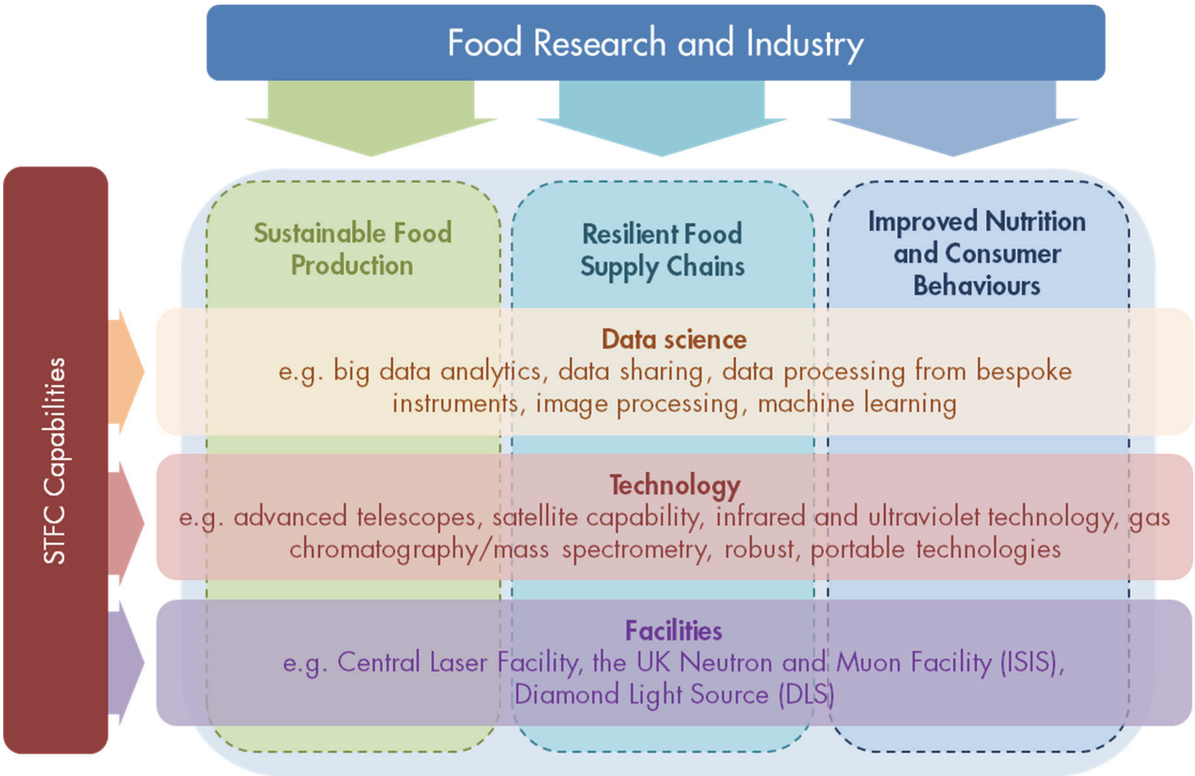
[7] Parliamentary Office of Science and Technology (2019).

[8] de Coninck et al. (2018).

[9] STFC Food Network Plus (2017).

[10] STFC Food Network Plus (2017).

Figure 1: Themes and technological areas addressed by the STFC Food Network+



Source: adapted from STFC Food Network Plus (2017)

The SFN facilitates collaboration between the STFC and agri-food actors through grant awards that provide early seed funding (up to £8,000) for the development of pilot projects that run for less than one year. It organises semi-regular 'sandpits' – interactive, multidisciplinary workshops – that bring together the network's diverse stakeholders in order to foster the generation of new ideas. The SFN has supported two rounds of project funding to date: one in 2018, which resulted in 20 funded projects, and one in 2019, which resulted in 22 funded projects.[11]

1.3. Study methods and limitations

This study was itself funded by a seed grant from the SFN. The funds enabled preliminary research to assess the potential of other SFN-funded projects to address climate change challenges in the food system. We reviewed a sub-set of the seed-funded projects, with a focus on those receiving grant funds in 2018 in order to review projects that have either been completed or are sufficiently mature. Projects were selected on the basis of relevance to the issue of climate change and GHG emissions, as well as familiarity of the project Principal Investigators (PIs) and Co-Investigators (CoIs) with the STFC and SFN processes and capabilities to date.

[11] STFC Food Network Plus (2019). In 2019, the UK Department for Environment, Food and Rural Affairs contributed towards the sandpit costs and scoping projects.

The review was largely informed by semi-structured telephone interviews, roughly 30 minutes long, with the following sets of SFN participants:

- PIs and CoIs of SFN-funded projects (some of whom are engaged in multiple projects).
- 'Champions' of SFN thematic areas [12] (i.e. those responsible for engaging with and promoting the SFN within relevant stakeholder groups) and 'Facilities Experts' who facilitate and promote collaboration with and access to the STFC's large facilities (all of those interviewed in this category were also project PIs and/or CoIs of projects).
- SFN 'Co-Investigators,' who form part of the SFN leadership.[13]

In total, the study team interviewed 19 individuals, including 17 grant recipients (of whom five are also SFN Champions or Facilities experts), covering 18 projects. The majority of interviews focused in-depth on projects funded in 2018, although relevant 2019 projects that interviewees were also engaged in were also included. Individuals were self-designated as part of the 'food network' or as 'STFC' representatives, although in practice some of these individuals could be classified under both categories. In total, we interviewed 14 food network representatives and 5 STFC representatives. The academic disciplines represented in this sample included, but were not limited to:

- STFC: astrophysics, computer science, analytical chemistry and engineering; and
- Food Network: environmental soil science, post-harvest technology, agroecology, management consultancy, plant science/biology.

Study limitations

In order to maintain a focused scope, the study targeted a selection of SFN projects that may demonstrate trends and potential, but is not comprehensive or systematic. Our study focused on those projects funded in 2018 in order to better assess the trajectory of projects over at least a one-year period. Climate change became an explicit area of focus for the network in 2019, so it is expected that further relevant projects will continue to emerge. Interviewees were often involved in multiple projects – some to a greater or lesser degree – and they could not always speak in depth about all of the projects in which they were involved. The study team also interviewed more food experts than STFC experts and industry representatives, primarily due to limitations in the sample size and the time constraints of the project. Both stakeholder groups would be important to significantly engage in any follow-on activity.

While the projects reviewed included an early analysis of potential for GHG emissions reduction, the scope and scale of this study did not allow for a full assessment of the implications and trade-offs related to emissions following the introduction of relevant technologies. This is particularly true for projects where effects on GHG emissions were indirect rather than direct – which was the case for the majority of projects we reviewed. This would need to be taken into consideration during any follow-on research.

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[12] 'Champions' are individuals charged with focusing on specific intersecting topic areas of the SFN (e.g. resilient supply chains, or data science), as well as to engage relevant stakeholders in the SFN and promote the SFN within those groups (STFC Food Network Plus 2019b).

[13] SFN 'Co-Investigators' form part of the SFN's leadership, providing strategic guidance (STFC Food Network Plus 2019c).

Finally, while this study focused primarily on the reduction of GHG emissions (i.e. mitigation of climate change), there is ample opportunity to extend the scope further to address how technologies are being applied through projects to enable the agri-food system to adapt to the risks associated with climate change (e.g. modelling focused on drought- or flood-resistant crops).

2. Findings

A review of the sample of 18 SFN-funded projects illustrated that STFC technologies and related facilities do have the potential to reduce GHG emissions in the agri-food sector. The majority of projects reviewed (83 per cent, or 15 of 18) exhibited the potential for indirect greenhouse gas reductions – mostly through efficiency gains either at the agricultural production stage or further along the supply chain – while a smaller number (17 per cent, or 3 of 18) had direct potential for greenhouse gas reduction.

The technologies most commonly applied within the projects reviewed included[14]: sensing and imaging (61 per cent, or 11 projects), large-scale data science (33 per cent, or 6 projects), and data sharing (22 per cent, or 4 projects). Of these, three projects used a combination of these three technology types. Other technology types applied included: citizen science (one project used this in combination with data sharing); distributed ledger technology (two projects, both of which used blockchain in combination with data sharing or other technologies); and cryogenics (one project).

Within the three elements of the broader food system focused on by the SFN (i.e. sustainable food production, resilient food supply chains, and improved nutrition and consumer behaviour), the majority of projects focused on primary production (61 per cent, or 11 projects), followed by supply chains (44 per cent, or 8 projects). Of these, two projects (11 per cent) focused on both production and supply. One project addressed consumer demand. Annex 1 provides information on the areas of focus for each project reviewed, both in terms of the STFC's technological capabilities and food system stages, as well as implications for GHG emissions. The following analysis discusses how different technology types, alone or in combination, were applied in projects, including promising potential future uses noted by interviewees.

[14] Technology types use categories as expressed/described by interviewees, and are not necessarily a reflection of the full spectrum of STFC's technological capabilities.

2.1. Several trends in the application of emerging technologies were identified from the review of SFN projects

The use of sensing and imaging technologies was one of the most common technological applications amongst the projects reviewed

Sensing and imaging technologies were integrated into more than half (11 of 18) of the SFN projects reviewed. These technologies were described by interviewees as having the potential to produce efficiency gains at many stages of the food system – particularly during agricultural production and throughout the supply chain – that may result in indirect emissions reductions. One of these projects applies STFC imaging technologies to better understand how biochar – a recognized zero emissions agricultural input – retains water and operates in damp environments (Box 1). This could enable the expanded application of biochar, with consequences for potential reduction of GHG emissions.

> **Box 1: Enhancing carbon sequestration in soil**
>
> Biochar is an input that can both contribute to soil health and help to sequester carbon, but its use to date has been limited to specific soil environments. *The Role of Biochar in Climate-Smart Agriculture* project applied the detailed imaging capabilities of the STFC to better understand the structure and water absorption capacity of biochar. This can inform a more detailed understanding of how biochar could operate in moist to wet soil environments, potentially supporting the extension of its use to moist UK soil or even potentially to rice paddy fields. This is particularly significant given relatively high methane emissions associated with rice production from flooded paddy fields.

Other projects examine how advanced sensing technologies can be used to identify poor-quality produce before dispatch, potentially resulting in reduced shipping of spoilt goods and avoidance of the GHG emissions associated with long-distance transport, as well as better disposal to reduce methane from food waste (Box 2). This could also result in spoilt goods being re-directed for other, more suitable purposes, enhancing systematic efficiency.

> **Box 2: Using sophisticated sensing technologies to assess quality in fresh produce**
>
> **Avocados** are popular but prone to spoilage that is invisible from the outside. The *Use of aroma volatiles profile for detecting mesocarp disorders in avocado fruit* project applies STFC technologies originally designed to assess organic compounds on comets (thermal desorption gas chromatography – mass spectrometry) to sense hidden fungal infections in avocadoes from the outside, without needing to open the fruit. Early detection of spoilage could lead to efficiency gains, reduce waste by avoiding distribution of affected avocados and potentially allow the re-directing of affected fruit to other uses (e.g. to produce avocado oil).
>
> **Fresh fruits and vegetables** represent a significant share of the food retail market but have a short shelf-life. The project *Scoping the feasibility of low-cost GC and GCxGC platforms for using volatile organic compound markers to assess quality of fresh fruit and vegetables throughout the supply chain* uses STFC sensing technologies designed for planetary exploration (thermal desorption gas chromatography – time-of-flight mass spectrometry (TD-GC-ToF-MS)) to detect quality changes in fresh produce. Designed for space missions, this STFC technology is highly portable, allowing *in situ*, rather than lab-based analysis, potentially extending its use by industry along the supply chain. This could lead to reduced food waste or transport of spoilt goods, indirectly impacting GHG emissions.

Several interviewees noted the potential to use STFC capabilities to miniaturise highly sophisticated imaging and sensing technologies – for example, small-scale sensors designed for the Mars rover – to enhance efficiency gains within the agri-food system that could further reduce emissions. Small-scale sensors could be placed directly in fields to help monitor crop health, and detect the onset or spread of disease before extensive damage is done. Similarly, sensors could monitor the performance of new crop varieties (e.g. those requiring fewer inputs, or that are more resilient to climate-related shocks) directly in the field rather than in controlled lab environments, leading to a more realistic understanding of their likely success and scalability. Interviewees also noted the potential for sensor technologies to support the move towards precision farming, which aims to decrease the overall use of inputs and the land required, potentially freeing up land for GHG reducing activities, such as bioenergy with capture and storage.

Large-scale data science capabilities and data sharing featured in several projects

The STFC's data science capabilities were integrated into 6 of the 18 SFN-funded projects studied for this report, and were one of the technologies used most frequently in combination with others. Projects primarily integrated the STFC's ability to format and analyse large, complex datasets through STFC-hosted infrastructure such as JASMIN,[15] which allows large-scale data processing.

While one project that applied data science involved the direct reduction of greenhouse gasses (reducing carbon emissions through vertical farming), the majority of projects applying data science had the potential to indirectly impact GHG emissions by tackling either input or supply-chain efficiencies. For example, data science capabilities have been applied in two projects that model the effects of climate change on staple crop yields (Box 3).

Box 3: Data science for climate-smart food systems

Vertical indoor farming – growing crops on vertical surfaces in climate-controlled environments – has the potential to reduce carbon emissions by maximizing outputs and minimizing inputs and land use. However, a large variety of information is required to optimize artificial climate control for indoor farms (e.g. lighting, nutrient delivery, temperature and humidity). The project *Making vertical farming stack up* uses STFC data-science expertise to inform how this data can be collected, stored, structured and processed. This can enable more precise measurement of vertical farming's carbon footprint and reduce carbon output per kilo of vertically farmed produce at scale.

Agricultural production can be significantly impacted by climate change through expected changes to temperature, rainfall and other factors. This can impact production of crops, such as wheat – a dietary staple in the UK and elsewhere – posing threats to future food supply. The projects *Forecasting Agricultural Crop Yields at National Scales (FACYNation)* and *SIM Farm* use STFC data-science capabilities to model how climate change will affect different staple crop varieties. This can help identify more resilient, less input-intensive crops, possibly reducing waste and GHG emissions.

[15] JASMIN is a large-scale data analysis infrastructure that combines fast storage, data analysis computing facilities, and satellite installation, primarily for the purposes of climate and earth-system modelling.

Cryogenics, distributed ledger technology and data-science applications also featured in the reviewed projects

Other reviewed projects included the application of technology such as cryogenics (Box 4), distributed ledger technology (Box 5), and data-science applications such as citizen science platforms originally used for the identification of galaxies (Box 6).

> **Box 4: Keeping food cold with cryogenics**
>
> Food loss is a major challenge – particularly for fresh products with a short shelf-life – in hot climates, especially where energy supply is unpredictable. Cryogenic and thermal insulation technologies designed for use in spacecraft have the potential to address cold supply-chain challenges, where infrastructure is otherwise unreliable, and could possibly result in energy efficiency gains. The *Application of Cryogenics to Optimise Cold Supply Chains for Agri-food products in India* project examines where these technologies could be applied within cold supply chains to the greatest effect. This could have the potential to mitigate GHG emissions indirectly (i.e. through reduced product loss), as well as through potential increases in energy efficiency.

Some combinations of technology showed particular promise, both in terms of increasing efficiency of the agri-food system and reducing GHG emissions

Several interviewees noted strong potential for increased sustainability within the food system, including GHG emissions reductions, through the application of promising technology combinations. This included the integration of **sensing technologies with data science**, allowing large amounts of detailed data from advanced sensors in agri-food systems to be processed and analysed. For example, one SFN project explores how a combination of sensors, imaging, and data analysis technologies can help monitor and predict environmental changes in shrimp farms in Indonesia, one of the largest global producers of shrimp. Efficiencies gained through reduced wastage could result in lower GHG emissions.

> **Box 5: Increased efficiency through self-organising supply chains**
>
> Data sharing, analysis, and distributed ledger technology have the potential, in combination, to optimize movements across complex supply chains. The project *Augmented Procurement Visibility – Developing the self-organising capability of agricultural procurement systems (APROV)* sets out a concept for how this combination of technologies can apply to food supply chains in practice, reducing energy costs associated with finding a market for goods and potentially reducing food waste.

Data sharing technologies were also applied in several projects, always in combination with another technology **(data science, sensing and imaging, and distributed ledger technology)**. One project combines technologies to assess opportunities to increase efficiencies across the agri-food supply chain Box 5. Another project applies data sharing and data science to monitor high-quality supply-chain surpluses in Thailand, and match available surpluses with the needs of vulnerable populations in real-time. This could result in reduced food waste by promoting the redirection of high-quality foods to populations in need.

Interviewees also noted the potential to apply combinations of these capacities beyond the pilot stage supported by SFN, and at greater scales within the food system. For example, large-scale placement of highly sensitive sensors across farming areas or along areas of the supply chain – for instance, food transportation, processing, retail and consumer use – could in theory generate enormous amounts of detailed information on many topics, including emissions, for analysis through large-scale data processing. This could potentially help produce, for example, a more detailed, evidence-based understanding of where in the food system, beyond agricultural production, GHG emissions are at their highest (complementing current estimates). This may also eventually integrate machine learning and artificial intelligence in order to provide better forecasting across agricultural production and supply-chain management, leading to potential efficiency gains, and also likely leading to a reduction in GHG emissions.

2.2. The majority of relevant SFN projects concentrated on the production and supply-chain stages of the agri-food system

The majority of projects reviewed focused on agricultural production (12 of 18 projects reviewed). This is consistent with our findings, which note that agricultural production is indeed the largest contributor to GHG emissions within the food system, according to current estimates. For example, one project addresses the management and reduction of agricultural pollutants through the application of new techniques for monitoring ammonia emissions on farms, an increasing issue of concern in the UK (Box 5).

Box 6: Applying astronomical technology to make agriculture more sustainable

Ammonia pollution has been rising in the UK, largely due to emissions from the agricultural sector, with negative implications for biodiversity and human health. The *Continuous Ammonia Monitoring for AGriculture (CAMAG)* project applies sensing technologies used in astronomy to enable continuous measurement of ammonia emissions from agriculture – something that has only been possible to date over defined periods of time. This new approach could enable better understanding of ammonia emissions dynamics and improved emissions management. While not a GHG, ammonia is linked to overall nitrogen management, including nitrous oxide (a powerful GHG). Loss of nitrogen through ammonia can also result in more fertilizer application to maintain yields.

Improving supply-chain efficiency (i.e. post-farmgate) was a strong focus amongst the reviewed projects (8 of 18 projects), all with potential indirect benefits for GHG reduction efforts. For example, early detection of product spoilage and non-intrusive monitoring of product quality (Box 2) presented clear opportunities to reduce waste and optimize energy inputs in the supply chain, as did the application of data science to improve the efficiency of procurement processes.

One project reviewed addressed consumer behaviour. This was done through a combination of citizen and data science to assess consumer perceptions of the impacts of different foods on health and the environment, explicitly through related GHG emissions (Box 6).

Box 7: Influencing consumer diets through citizen science

Consumer preferences for more sustainable diets have the potential to drive agri-food activities. The project *Piloting Zooniverse* uses a citizen-science platform developed to identify galaxies to help understand how consumer perceptions of calories and carbon emissions associated with specific foods differ from the actual values. The technology allows for both data collection and consumer education, with the potential to both inform policymakers regarding consumer perceptions and prompt more sustainable food choices through consumer education.

2.3. Interviewees noted opportunities, considerations and constraints in the development and implementation of SFN-funded projects

Interviewees, including grantees and Network CoIs, noted important potential opportunities and constraints that are relevant to further work in this area.

Most interviewees highlighted the importance of **physically bringing together members of different communities** (STFC, academic, industry) through the SFN in order to catalyse the application of emerging technologies from one domain (physics and large facilities) in another (the agri-food system). Many projects began through incidental interactions at SFN events, and likely would not have otherwise occurred, although some project ideas were conceived of in advance, through previous research. Given the high degree of separation amongst disciplines, in-person events – complemented by the efforts of SFN Champions – were viewed by many as an essential step towards matching food systems challenges with technologies in other domains. Some interviewees noted that, for some researchers, working outside of one's discipline may not be immediately attractive, and suggested that case-studies highlighting the potential impacts of such collaboration could be a helpful incentive to engage more in inter-disciplinary work.

Many interviewees noted **funding** to be a key constraint to further development of SFN concepts, and at times to be an incentive for participating in the SFN or projects themselves – particularly given competing time pressures faced by project PIs and CoIs, as well as by the STFC champions. While the objective of the SFN is to provide small amounts of seed funding to kick-start collaborations, many noted difficulties in accessing further funding, for instance to help build prototypes based on concepts developed through seed funding, or to bring pilot projects to a stage where they may attract potential commercial investment. Others noted that the SFN helpfully brought in potential further funders, including the UK Department for Environment, Food and Rural Affairs and UK Research and Innovation (UKRI). Further funding of projects to date has generally been either follow-up funding from the STFC of around £10k–25k and/or the Global Challenges Research Fund (UKRI), with the least being around £25k and the most being around £800k.

SFN projects tended to focus on specific – though still quite broad – **areas within the food system**, with work devoted to consumer demand emerging as an area with the least focus (of the 18 projects studied in this report). However, from a GHG perspective, consumer demand is a relevant driver of emissions from the rest of the system. While this may be due to the relatively small number of projects funded and reviewed overall, some interviewees speculated that the concentration of projects on the production and supply segments of the food system may reflect the research interests of individual network members, which tend to be more focused on physical rather than social sciences. Others noted that while demand is an important element of the food system, its linkages to sustainability (including but not limited to GHG emissions) tend to be more diffuse and less directly well-understood than at other points of the food system (e.g. factors that cause behavioural change), resulting in a bias towards interventions with more readily measurable impacts.

A few interviewees noted the need to consider the applicability of technology for all food systems actors, including farmers and small businesses. This would require an eventual focus on **cost** of technological advances within pilot projects. This would ultimately inform the applicability, scalability, and usefulness of concepts developed through the network.

All of the interviewees agreed that the network has provided an opportunity to showcase the importance of **multi-disciplinary partnerships**. Many STFC Coordinators and Champions who were interviewed agreed that projects so far have utilised only a small portion of the capabilities available and emphasised that there remains significant potential to expand the application of STFC technology within the food system.

3. Conclusions

Findings from this exploratory study demonstrate that that there is potential for technological innovations developed through the STFC to facilitate climate-change mitigation when applied to the agri-food sector

In particular, the study identifies promising types and characteristics of technology and their combinations (e.g. data science, and sensing and imaging technologies), as well as early indications of entry-points within the food system for their adoption (e.g. within the broad area of agricultural production) to contribute to the reduction of GHG emissions.

While these findings are based on a small sample of projects, they are nevertheless indicative of emerging trends and promising avenues for further exploration, as well as potential challenges in the application of technologies developed in one sector to another. These opportunities and challenges can be explored more systematically and in greater depth.

For example, technology trends could be identified by developing a framework consisting of important issues within the food system that need to be addressed, and then assessing the relevant political, economic, social and technological/scientific factors affecting each of these issues. A review of emerging technologies and applications of relevance to those issues could be undertaken, considering how they relate to the wider context in which they could be developed to address food systems challenges (i.e. the political, economic and social factors alongside the technological). These technologies could then be considered in terms of their potential impact on climate change, as well as the likelihood that they could be successfully applied to food systems challenges. Together, this analysis could provide insight on those technologies (or combinations of technologies) that show greatest promise as the focus of a future research programme (or indeed, multiple research programmes). This could be delivered through a combination of methods, including expert interviews, crowd-sourcing and rigorous review of relevant academic and grey literature.

Such work could ultimately form a larger-scale foresight exercise to more specifically identify relevant emerging technologies.[16] This could remain within or potentially extend beyond STFC areas of work and support the proactive identification of nascent and potentially disruptive technologies that may be applied across the agri-food system to reduce GHG emissions. It could inform policy-relevant recommendations for the further development of promising examples. Such exercises have been successfully applied by

[16] Including analytical techniques that seek to better understand potential future developments (RAND Corporation 2019).

RAND Europe within the transport, defence and security sectors as well as recently in the context of food safety, to generate a better understanding of the risks, opportunities and likely impacts of new technologies.

The potential of technological developments to facilitate climate emissions reductions is particularly important given the contribution of food systems to GHG emissions globally and within the UK

In the context of the UK's commitment to bring emissions to 'net zero' by 2050,[17] agriculture has been highlighted as a sector where emissions reductions have lagged behind and require accelerated progress. Food consumption has been identified as an area where individuals can do more (e.g. reduction in waste) to contribute to emissions reductions.[18] Globally, agriculture has become an increasing area of focus within international discussions on climate action.[19]

Building on the early research conducted during this exploratory study, a further examination of promising technologies and their potential impacts on agri-food GHG emissions could help to address this challenge by:

- Informing the development of future emissions scenarios by demonstrating which technologies may have the highest levels of impact and how;
- Guiding research and investment decisions on technologies (or technology types) that show the most promise; and
- Informing decision-making on the enabling environment for the application of such technologies.

As demonstrated through this exploratory study, technological advancement has a pivotal role in helping to address complex issues beyond what has been considered possible by using traditional means, including within the agri-food system. A fuller understanding of the potential of technological solutions could help inform innovative decision-making and accelerate progress. The findings in this paper may serve as a point of departure for this work.

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[17] UK Government (2019).

[18] Committee on Climate Change (2019).

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Annex A. Summary of reviewed SFN projects

Table 1: Reviewed SFN projects by technology type, food system area and potential impact on GHG emissions

	Technology						Food system			GHG reductions	
Project topic	Data science	Sensing & imaging	Citizen Science	DLT/ Blockchain	Data sharing	Cryogenics	Production	Supply	Consumer behaviour	Direct	Indirect
Forecasting agricultural crop yields	✓										✓
Vertical farming	✓						✓			✓	
Continuous ammonia monitoring		✓					✓				✓
Sensing specific disorders in avocadoes		✓						✓			✓
Non-destructive sensing of avocado fruit quality		✓						✓			✓
Low-cost quality sensing of fresh produce		✓						✓			✓
Consumer perceptions (Zooniverse)			✓		✓				✓	✓	
Infrared to enhancing cattle pregnancy success		✓					✓				✓
Automating quality and manufacturing efficiency		✓					✓	✓			✓
Safe, sustainable shrimp aquaculture (Indonesia)	✓	✓					✓				✓
Automating food surplus data (Thailand)	✓				✓			✓			✓
Data-driven agri-food supply chains (China)	✓	✓		✓	✓		✓	✓			✓
Cryogenics to optimise cold supply chains (India)						✓		✓			✓
X-rays for arsenic detection in rice		✓									✓
Data sharing for improved procurement				✓	✓		✓	✓			✓
Modelling the resilience of wheat varieties	✓						✓				✓
Extending the use of biochar		✓					✓			✓	
Satellite-based soil organic carbon observatory		✓					✓				✓
Total	6	11	1	2	4	1	11	8	1	3	15