February 2024

Transforming Food Production

Final Evaluation

Annexes

SQW

Contents

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Annex A: Detailed programme information

Assumptions underpinning the TFP logic model and theory of change

A.1 Below we present assumptions underpinning TFP logic model in Table A-1, and potential enabling factors, barriers and external drivers that were tested during the evaluation.

Table A-1: ***Assumptions***

Short term and intermediate outcomes and benefits

- Collaborative approach and effective knowledge exchange between project partners lead to "better" solutions
- Projects are successfully able to prove/demonstrate viability and potential benefits of technologies/solutions (de-risked sufficiently within the lifetime of the TFP funding in order to secure follow-on investment / reach the market / address previous blockages / encourage adoption etc)
- Projects engage with relevant extension services/follow-on support/ongoing private sector R&D as required
- IP is protected appropriately
- Projects develop a sound understanding of the target market, and partners are able to develop relevant networks (UK/globally) in these markets
- Engagement with end-users (and intermediaries) in demonstration activities*
- Success of projects leads to new interest, investment and entrants into novel food production areas*
- Alignment with UK and Overseas Government strategic priorities*

Long-term impacts and benefits

- Knowledge is shared effectively / openly / widely, via effective dissemination mechanisms
- Agritech firm has the capacity and capability to take products/services to market (ahead of global competition)
- Agritech firm has motivation and capability to scale-up the business
- New technologies developed are not overtaken by wider market developments
- High value jobs are created via the growth of agritech firms (displacement of jobs at lower agriculture skills levels)

- Integrated technology solutions are more likely to be adopted than single/narrow technologies
- Wider agricultural sector has the awareness, willingness and capability (financial and skills) to adopt new technologies; and wider demand-side adoption barriers addressed
- New technologies/solutions are aligned to market need and demand (UK and globally), affordable, and have a sufficient ROI to justify investment to adopt
- New technologies are sufficiently substantive / establish sufficient "critical mass" / have broad application to ensure widespread use and a demonstrable impact on sector performance
- Effective feedback loops to ensure that knowledge generated during TFP informs ongoing innovation activity in wider innovation landscape and policy development

*Source: SQW. Note: * not relevant to all strands*

A.2 In addition to the assumptions above, Table A-2 summarises key mechanisms that are expected to lead to changes/outcomes/impacts presented in the TFP logic model, based on a review of project applications. These mechanisms were tested during the evaluation.

Table A-2: Anticipated causal mechanisms and routes to impact

- **Grant funding** is a mechanism to de-risk and lever match funding for TFP project activities, and progresses technologies/solutions sufficiently to de-risk follow-on investment/take technologies/solutions to market
- **Multi-disciplinary collaboration**, including end-users, and a focus on **integrated technologies** leads to more innovative and 'fit-for-purpose' technologies/solutions
- A **systems approach involving actors across the value chain** in collaborative R&D provides routes to market, e.g. key customers for the end product, intermediaries for key customers (e.g. via licensing), or (particularly in the international strand) access to overseas markets
- Effective **knowledge exchange networks/diffusion mechanisms** and engagement with relevant actors (including intermediaries) supports demand-side awareness/uptake
- **Business growth** is driven by direct sale of technology/solution products, platform subscriptions, licensing and services – this includes new technology/solutions taken to market and/or widening existing market reach
- **Benefits to participating organisations** are realised via a range of routes: validation of technology/solution at an economically viable commercial scale; improved efficiency/reduced costs of technology/solution production leading to more affordable price in wider market and increased adoption, and/or increased profit margin/viability of novel production systems; and building market awareness/positioning in UK or overseas

A.3 There are also a series of external drivers and factors that may influence the performance of the programme, which the evaluation considered, including:

- Variability in the stage of development and level of maturity across agricultural sub-sectors, particularly in terms of appetite to change and technology adoption
- Wider system-related factors that influence the success of TFP projects, and/or unintended consequences arising from TFP projects on the wider system that have feedback loops/knock-on implications for TFP's overarching goals
- Economic conditions (and the influence on investment in innovation and ability to adopt)
- External shocks, e.g. Covid-19 & Brexit, and implications for agriculture on both the demand-side and supply-side (influencing behaviours, investment, attitudes in the sector in relation to the take-up of new technologies and solutions)
- General labour and skills availability (in both the agritech and wider agricultural sector)
- Prices, exchange rates, profit margins in agricultural sector, and global demand for end products
- Policy and regulatory changes/developments, including the implementation of the Agriculture Bill and National Food Strategy, and the phasing-out over the programme delivery period of Direct Payments to farmers and phased introduction of a new payments system as part of the wider Agricultural Transition Plan 2021 to 2024[1]
- UK and Overseas Government strategy and priorities for international trade
- The availability of other sources of R&D funding, including complementary and potentially duplicating schemes, and wider policy interventions/levers/actors also seeking to improve productivity/reduce emissions in the agricultural sector
- Weather and seasonality (influencing delivery and potentially ability to realise outcomes/impacts, at least in the short term)
- Public opinion, particularly in relation to how food is produced and acceptance of technological developments and alternative approaches to food production.

Factors affecting the adoption of agritech innovations

A.4 In addition to enabling the development and commercialisation of agritech innovations, accelerating their adoption by food producers is essential. Despite the UK being home to world-leading agri-food technology expertise and R&D, translating new innovative products and process

[1] The Path to Sustainable Farming: An Agricultural Transition Plan 2021 to 2024 (see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/939925/agricultural-transition-plan.pdf)

into changed behaviours and practices on farms is a significant challenge, reflecting both supply-side and demand-side factors, as illustrated in Table A-3.

Table A-3: Factors affecting the adoption of agritech innovations

Supply-side factors:	Demand-side factors:
• A reluctance to disseminate knowledge during the R&D process and prior to commercialisation in order to retain a competitive edge • A knowledge exchange landscape that is often described as "fractured" and weak, where the diversity and complexity of the sector makes the diffusion of new innovations particularly difficult • The importance of intermediaries (e.g. sector bodies, advisors), providing a bridge between the science/research base, agritech firms, equipment manufacturers and input suppliers and the farming community • The extent to which the supply chain is actively involved or consolidated (e.g. in fruit co-operatives): technology is developed/adopted more quickly where privately-led supply chains or vertically integrated routes have the capacity and resources to develop, trial and roll out solutions which work.	Barriers to adoption vary across geographies and sub-sectors, but commonly cited issues include: • Information failures: farmers are unaware of new innovations, potential returns, how to access them or more fundamentally the need for change • Risk aversion and path dependency, compounded by succession/inter-generational challenges • Confidence, education and attitudinal issues • Farm size, cost and a lack of capital to invest in new products/processes (especially where profit margins are low and/or highly variable), often combined with longer payback periods • A lack of demonstration sites on commercial farms which are well promoted and properly costed • Skills issues, both in terms of management practices, and technical capabilities to operate new systems effectively or process/interpret data • Technical issues, such as system/platform compatibility, broadband connectivity, and mobile reception/reliability • The inability of farmers to fully capture positive externalities through adopting innovative technologies is significant (e.g. food security, climate change and environmental sustainability) leading to under-investment

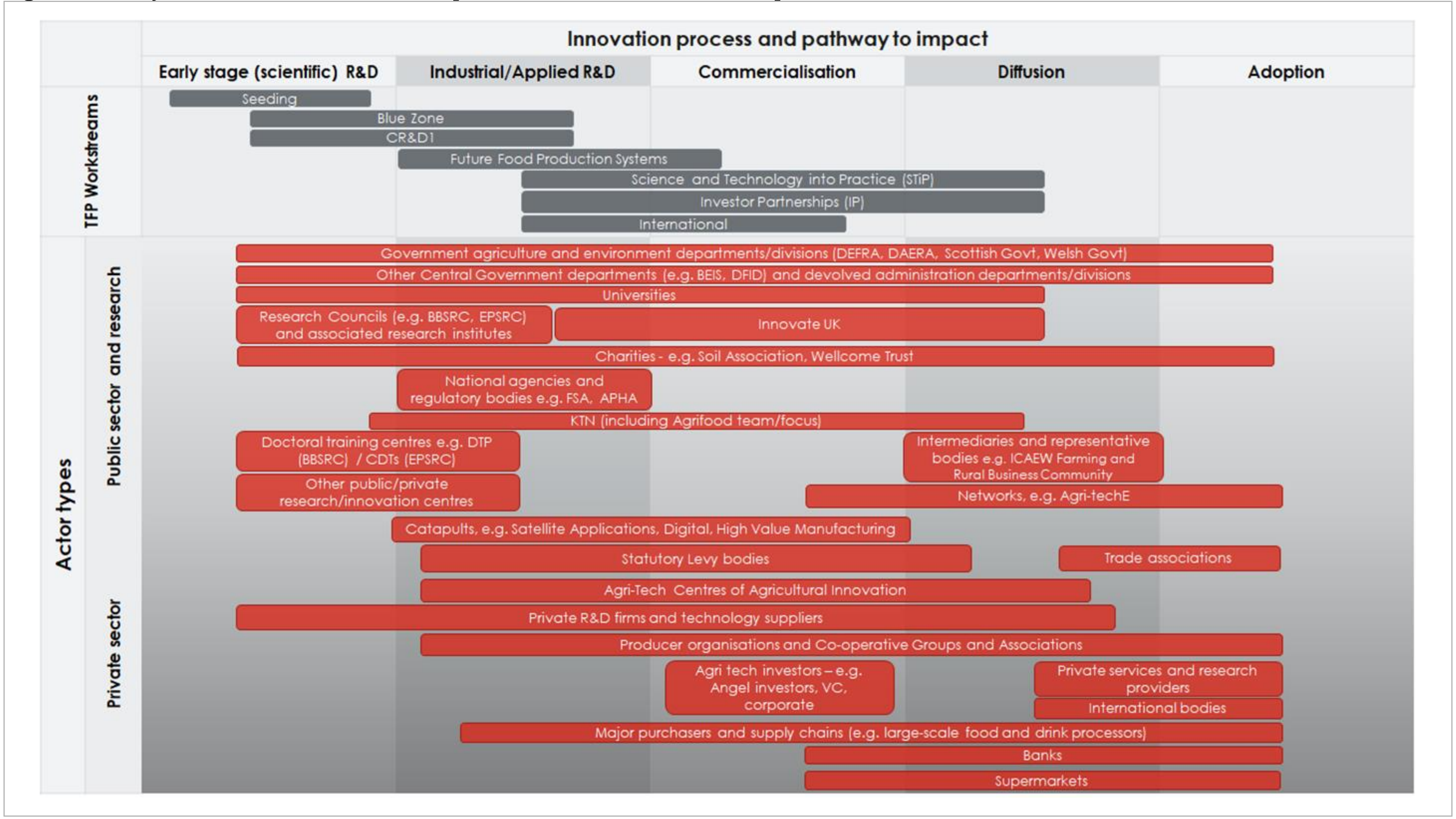
Source: SQW from various sources[2]

Food production innovation landscape

A.5 The diagram below sets out the key actors involved in the food production innovation landscape, providing an overview of each actor's remit and role across the R&D/innovation process.

[2] Sources include: Policy Links, University of Cambridge (2016) Making 'smart specialisation' smarter: an industrial -innovation system approach; and AHDB (2018) Understand how to influence farmers' decision-making behaviour; Irish Farmers Association (2019) Digital Agriculture Technology Adoption & Attitudes Study; Defra (2020) Farm Practices Survey; FDSC (2019) Preparing for a changing workforce: A food and drink supply chain approach to skills; Soto Embodas et all (2019) The contribution of precision agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU

Figure A-1: Key actors involved in the food production innovation landscape

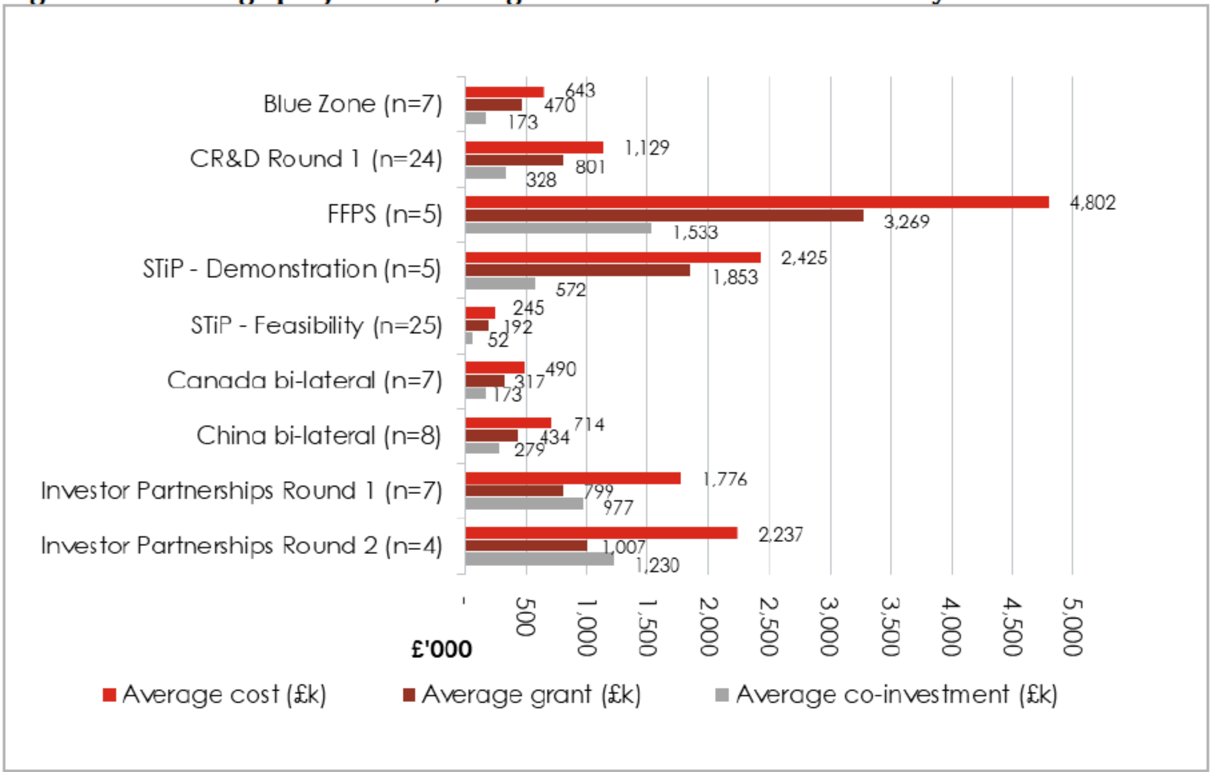


Source: SQW

Additional monitoring data analysis

Characteristics of projects

Figure A-2: Average project cost, TFP grant offer and co-investment by strand



Source: SQW analysis of TFP monitoring data to October 2023. Note excludes Seeding Awards.

Technology focus

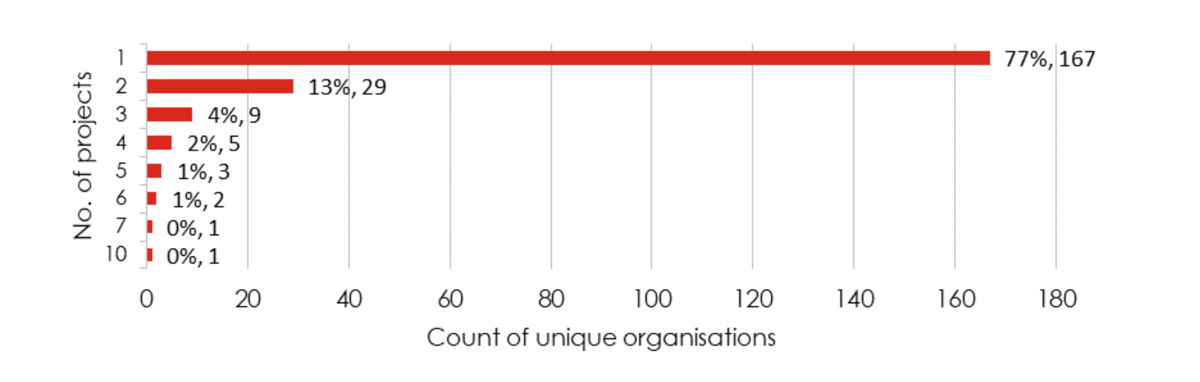
Table A-4: Projects by primary technology

Broad technology area	% of all projects (n=92)	% of total TFP funding allocation (£68m)
Biochemicals	3%	3%
Advanced plant or animal breeding, Genetics and Genomics	4%	2%
Novel food production systems or sources	8%	7%
Data recording/collection systems or technologies	20%	20%
Automation / control systems or technologies	26%	25%
Data analytics / decision support systems or technologies	39%	43%

Source: SQW analysis of TFP monitoring data to October 2023. This data excludes Seeding Awards.

Characterising organisations involved

Figure A-3: Number of projects per unique organisation



Source: SQW analysis of TFP monitoring data October 2023

Annex B: Detailed methodology

Overview of methodology

B.1 Figure B-1 provides an overview of the approach taken to each phase of the evaluation. In the paragraphs that follow, we provide further detail on the methodology for Phase 4 (Progress evaluation) and Phase 5 (final impact evaluation).

Figure B-1: Evaluation overview

Source: SQW

Methodology in Phase 4

B.2 The table below provides further detail on the workstreams undertaken for Phase 4.

Table B-1: Phase 4 methodology

Name	Description
Monitoring Data Analysis	Monitoring data analysed included data from UKRI, including project funding and expenditure data and TFP monitoring officer RAG reports. In addition, a headline summary was undertaken of project in-flight and closeout surveys – however, the relatively small number of responses limited the ability to analyse these.
Review of programme documentation	This included board minutes where the TFP programme was discussed and monitoring officers showcased materials.
Analysis of contextual data	Contextual and sector data were analysed to give a broader understanding of the TFP context and performance, including both static and longitudinal analysis. Eight key sources were used, including: • Agriculture in the United Kingdom, Defra 2022 • Environmental Accounts, ONS 2022 • Annual Survey of Hours and Earnings, ONS 2021 • Community Innovation Survey, BEIS, 2021
Stakeholder consultations	Seven in-depth stakeholder consultations, of which two were with representatives of the TFP programme team and five were from wider stakeholder (UKRI, Defra and Sector representatives).
Representative consultations	37 in-depth consultations with those working on projects. This consisted of 31 project leads and six project partners and were distributed across a range of project strands, technology areas and project performance. Roughly one-third of all projects were represented, and those projects accounted for approximately half of all funding committed and spent by May 2022.

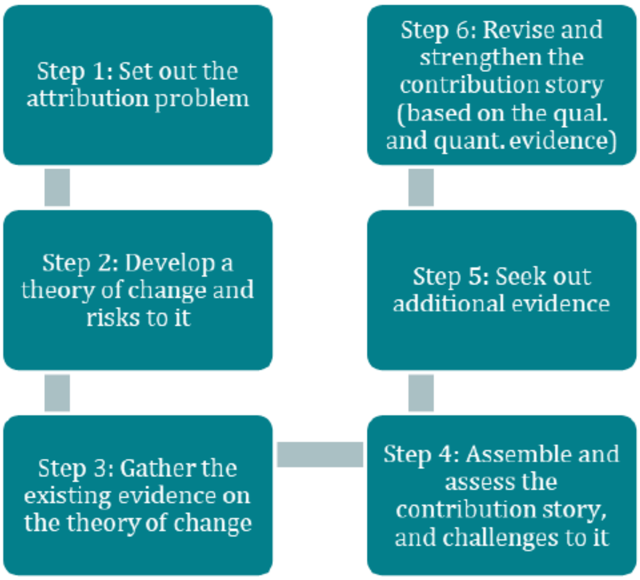
Source: SQW

Detailed methodology in Phase 5

Contribution analysis

B.3 The process is based on a six-step method to gather evidence and develop a 'contribution story', summarised below. In this evaluation, Steps 1 and 2 were completed through the evaluation framework and baseline. Evidence was then gathered through the process and progress evaluations (Steps 3 and 4). During the latter, we developed an initial "contribution story" for each of the three categories of impact evaluation RQs (direct outcomes and impacts; indirect/longer-term impacts; and strategic/system level effects) based on the quantitative and qualitative evidence gathered. Further evidence was then gathered during this final impact evaluation to revise and strengthen the contribution stories (Steps 5 and 6).

Figure B-2: Six steps of Contribution Analysis



Annex B: Source: Mayne, 2008, Contribution Analysis: An Approach to Exploring Cause and Effect, ILAC Brief 16

Evaluation workstreams

B.1 The table below provides further detail on the workstreams undertaken for Phase 5.

Table B-2: Phase 5 methodology

Name	Description
Monitoring Data Analysis	For all funded projects, a variety of different monitoring data sources were analysed to form a full picture of the programme. These were: • UKRI Project Monitoring Reports – in which projects were scored from one to five in each of six categories • Project in-flight surveys • Project end surveys – only applicable to projects that have closed • Project close out reports
Stakeholder consultations	In depth interviews completed with project stakeholders, 10 internal (UKRI) and 12 external (see Annex C)
Survey with beneficiaries Wave 2	A census style telephone survey that all project leaders and collaborators on successfully funded projects were approached and asked to complete. There were 74 responses, consisting of 32 project leads and 42 collaborators, a response rate of 38%. This sample included 51 projects where there had been at least one project lead and/or collaborator responding, over half of all the projects in scope. All strands were represented in the sample and the sample was broadly representative of the population in terms of factors such as . their role in the project, their business size etc. However, it was was slightly underrepresented in terms of academics.

Name	Description
Survey with unsuccessful applicants Wave 2	A census style telephone survey where all project leads and collaborators on projects that were not funded were approached and asked to complete until the target number of respondents had been reached. This built on a previously conducted Wave 1 survey. The sample had 119 responses, composed of 40 project leads and 79 project collaborators. In terms of characteristics e.g. actor type (business/academic/other) and business size, the survey respondents were representative of the larger population. Of the 119, 35 also completed the Wave 1 survey and a further 69 respondents only completed the Wave 1 survey, giving a total unique respondent count across both surveys of 188.
Wider Sector Survey Wave 2	A telephone survey to members of the wider agricultural community to ascertain awareness and adoption of innovative technologies. The wave 2 survey follows a Wave 1 survey in July 2021 – only organisations that responded to the Wave 1 survey were contacted at the wave 2 stage. Of the 304 that responded to the Wave 1 survey, 126 responded to the Wave 2 survey – a response rate of 41%.
Impact tracing case studies	Drawing on beneficiary survey findings, 22 projects were sampled for in-depth case studies. The focus of the case studies was to understand how and why TFP funding had helped projects progress technologies and move towards commercialisation and adoption, and factors that had helped or hindered this, to test the theory of change at a project level, Sampling was undertaken to ensure a spread across strands, technology type, scale and location of projects. Each case study involved a series of consultations with members of the project team – and where possible end users who had trialled or adopted the technology.
Strategic case studies	Two strategic case studies were undertaken on the Alternative Proteins Roadmap and the Investor Roundtable. This involved a review of documentation and a small number of consultations with stakeholders.
Technology tracing exercise	The technology tracing exercise focused on four technology areas that were well aligned with the focus of TFP: robotics in harvesting, artificial intelligence, alternative proteins and controlled environment agriculture. In the baseline, a desk -based review of data and documents was undertaken to inform a short 'technology statement' for each of the four areas above. This was updated in Phase 5 to understand change over time. Four two-hour virtual workshops where then held with experts in each technology area to provide feedback on the 'technology statements' and discuss the potential contribution of TFP to maturing technologies in each area. Through this process, we engaged with 31 experts, including academics, business, and sector experts.
Econometric Analysis	See Annex G below.
Quantitative futures analysis	See Annex G below.

Name	Description
Qualitative futures analysis	This involved synthesis of evidence gathered across the evaluation workstreams and consideration of (a) key trends, drivers of change and external factors influencing diffusion/take-up of agricultural precision technologies to 2030, (b) the Alignment of TFP's activities and outcomes to these issues; and (c) if and how TFP will contribute to change over the longer term to 2040 (especially net zero), including underpinning assumptions, uncertainties, opportunities. This was then discussed at an internal team workshop including partners from IfM and Martin Collison Associates.
Sector projections	Cambridge Econometrics updated projections, which helped to inform the qualitative futures analysis above
International Review and horizon scanning	This involved a high level, desk based review of trends in the UK agriculture sector in an international perspective and in international "hotspots" for agritech technologies, and a headline horizon scanning to inform the qualitative futures analysis above,

Source: SQW

Coverage of monitoring data

B.2 The coverage of monitoring data on outputs and outcomes is outlined below. Overall, in-flight survey data is patchy and dated. Although there were a large number of survey responses, many were not complete. Most completions (72%) were in 2021 and therefore dated by the time of the final evaluation.

Table B-3: Coverage of monitoring data

	In-flight e-survey data	Project end e-survey data (closed projects only)	Close out reports (closed projects only)
Total number of responses	426	83	176
Total number of projects with a response (partner or lead)	51	29	58
Total number of unique responses (i.e. one per organisation per project)	136	69	51

Source: SQW analysis of monitoring data

Representativeness of beneficiary survey respondents in Phase 5

B.3 There were 105 respondents to the Wave 1 (baseline) survey and 74 respondents to the Wave 2 (final impact) survey. As shown in Table B-4, some individuals responded to one survey only, whilst others completed both surveys. A total of 135 unique organisations responded across the two surveys.

Table B-4: Beneficiary survey coverage

All Wave 1 and Wave 2 Respondents	No. of survey respondents
Total number of respondents Wave 1	105 (45% response rate)
Total number of respondents Wave 2	74 (38% response rate)
Breakdown by survey completion	
Completed Wave 1 and Wave 2 surveys for same project	39
Completed Wave 1 and Wave 2 surveys for different projects	5
Completed Wave 1 only	61
Completed Wave 2 only	30
Total unique respondents to Wave 1 and Wave 2 surveys	**135**

Source: SQW analysis of baseline and final evaluation surveys

B.4 In total, 74 beneficiaries responded to the Wave 2 (final impact) survey. The following tables set out results of the representativeness analysis undertaken to compare details of the profile of respondents and projects against the full population of beneficiaries and projects. As shown in Table B-5, most respondents are businesses, which is representative of the wider beneficiary population.

Table B-5: Beneficiary organisation type (survey vs population)

	Survey (n=74)		Population (n=212)*	
	No.	**%**	**No.**	**%**
Business	65	88%	161	76%
Academic	4	5%	39	18%
Other	5	7%	12	6%
Total	74	100%	212	100%

Source: SQW analysis of TFP monitoring data and IFF survey data
** The beneficiary population excludes withdrawn organisations, and organisations that are involved in Seeding projects only.*

B.5 The survey respondents provided a good representation of the wider population in terms of the roles held (Table B-6). For example, 43% of the survey population (32/74) are leading a project compared to 39% in the beneficiary population (83/212).

Table B-6: Project role (survey vs population)

	Survey (n=74)		Population (n=212)	
	No.	**%**	**No.**	**%**
Lead[3]	32	43%	83	39%
Collaborator	42	57%	129	61%
Total	74	100%	212	100%

Source: SQW analysis of TFP monitoring data and IFF survey data

B.6 The 74 beneficiaries surveyed represented 51 different projects, which is over half of all TFP projects in the scope of the evaluation. Project representation means that at least one organisation involved in the project was surveyed (either a lead or a collaborator). As shown in Table 6, there is reasonably good coverage across all of the competitions, although it is lowest for the Investor Partnerships with only three of the 11 different projects being represented. The 51 surveyed projects account for £39.0m (or 57%) of the TFP funding allocated across these competitions.

Table B-7: Number and proportion of projects surveyed (lead and/or collaborators)

	Survey		Population	
	No. of respondents	**No. of projects represented**	**No. of projects**	**% of projects surveyed**
Blue Zone	2	2	7	29%
CR&D1	25	16	24	67%
FFPS	8	3	5	60%
STiP (feasibility)	21	16	25	64%
STiP (demonstration)	6	4	5	80%
International	9	7	15	47%
Investor	3	3	11	27%
Total	74	51	92	55%

Source: SQW analysis of final evaluation survey

B.7 Of the 74 beneficiaries surveyed, **32 were project leads and 42 were collaborators only**. The 32 leads represent 35% of the projects funded through the programme.[4] As shown in Table B-8:, **at least one lead was surveyed across all of the strands**.

[3] For the wider population, this category includes organisations who are both leads and collaborators.
[4] Excluding seeding.

Table B-8: Number and proportion of projects surveyed (leads only)

	No. of lead respondents	Total no. of projects funded	% of projects represented by leads
Blue Zone	2	7	29%
CR&D1	9	24	38%
FFPS	2	5	40%
STiP (feasibility)	8	25	32%
STiP (demonstration)	3	5	60%
International	5	15	33%
Investor	3	11	27%
Total	32	92	35%

Source: SQW analysis of final evaluation survey

Representativeness of UA survey respondents in Phase 5

B.8 There were 104 respondents to the Wave 1 (baseline) survey and 119 respondents to the Wave 2 (final impact) survey. As shown in Table B-4, some individuals responded to one survey only, whilst others completed both surveys. A total of 188 unique organisations responded across the two surveys.

Table B-9: UA survey coverage

All Wave 1 and Wave 2 Respondents	No. of survey respondents
Total number of respondents Wave 1	104 (20% response rate)
Total number of respondents Wave 2	119 (20% response rate)
Breakdown by survey completion	
Completed Wave 1 and Wave 2 surveys for same project	35
Completed Wave 1 only	69
Completed Wave 2 only	84
Total unique respondents to Wave 1 and Wave 2 surveys	**188**

Source: SQW analysis of baseline and final evaluation surveys

B.9 In total, 119 beneficiaries responded to the Wave 2 (final impact) survey. The following tables set out results of the representativeness analysis undertaken to compare details of the profile of respondents and projects against the full population of UAs and projects. As shown in the following tables, the Wave 2 survey respondents were broadly representative of the full cohort of unsuccessful applicants in terms of actor type (business, academic or other), role in the project (collaborator or lead), and TFP strand.

Table B-10: UA organisation type (survey vs population)

	Count – Wave 2 Survey	Proportion - Wave 2 Survey	Proportion – All UAs
Business	109	92%	91%
Academic	3	3%	5%
Other	7	6%	4%
Total	119	100%	100%

Source: SQW Analysis of survey and monitoring data

Table B-11: Project role (survey vs population)

	Count – Wave 2 Survey	Proportion – Wave 2 Survey	Proportion – All UAs
Lead	79	66%	69%
Collaborator	40	34%	31%
Total	119	100%	100%

Source: SQW Analysis of survey and monitoring data

Table B-12: TFP Strand (survey vs population)

	Count – Wave 2 Survey	Proportion – Wave 2 Survey	Proportion – All UAs
220 - Productive and Sustainable Crop and Ruminant Agricultural Systems	33	28%	26%
ISCF Future food production systems	27	23%	25%
International*	1	1%	5%
SMEs Transforming food production: Series A Investor Partnership round 2	7	6%	3%
ISCF TFP science and technology into practice: demonstration	40	34%	31%
ISCF Transforming Food Production Science and Technology into Practice FS	11	9%	10%
Total	119	100%	100%

Source: SQW Analysis of survey and monitoring data

**This is the combination of 'UK-China: precision for enhancing agricultural productivity' and 'UK-Canada: enhancing agricultural productivity and sustainability'*

Coverage of project level case studies in Phase 5

B.10 Table B-13 sets out coverage and progress of the project level case studies undertaken during Phase 5.

Table B-13: Case study coverage

TFP Strand	No. case studies
Collaborative R&D Round 1	6
Future Food Production Systems	1
Science and Technology Into Practice – Feasibility	6
Science and Technology Into Practice – Demonstration	3
International Bi-Lateral interventions – UK-China	1
International Bi-Lateral interventions – UK-Canada	3
Investor Partnerships	2
Total	**22**

Source: SQW

Annex C: Consultees

Consultations

Table C-1: Stakeholder consultees (Phases 4 and/or 5)

Name	Organisation	Phase 4 or 5
[redacted]		
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Name	Organisation	Phase 4 or 5
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

*Source: SQW. Note: * consulted for the strategic case studies*

Technology tracing workshop participants

Table C-2: Technology tracing workshop participants

Name	Organisation	Type
[redacted]		
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

*Source: SQW *Provided written feedback*

Annex D: Additional analysis of Beauhurst data

About Beauhurst

D.1 Beauhurst is a database of business performance and public/private investment data for potential high-growth companies in the UK, including UKRI grant recipients.[5] Alongside headline data on around 79,000 UK registered companies, more detailed information is held on 'tracked' companies, including data on equity and loan investments across stages (seed, venture, growth etc.).[6] Companies are tracked if they meet one or more of the following 'triggers': the company has secured equity/venture debt investment; it has been or is a 10% or 20% scale up; it has been spun-out of a UK university or Higher Education Institution (HEI); it has completed one of the UK's top accelerator programmes; it has completed a management buy-in/out; it has been listed on one of the UK's top high growth lists; or has received an innovation grant[7], for example from UKRI, H2020, FP7.

- The database includes the following key indicators:
- For all companies captured in the database:
- Incorporation date
- Companies House status
- Standard Industrial Classification(s)

D.2 For tracked companies:

- Beauhurst stage of evolution
- Latest employee count
- Beauhurst's tailored sector definitions
- Public and private investment secured (number, value, source and timing)
- Beauhurst tracking reasons

[5] Those in receipt of £100k or more per instance of grant support.
[6] 'Tracked' means that Beauhurst gathers detailed data on the firm, including investment over time, in addition to basic Companies House data.
[7] As above, of £100k or more.

Analysis purpose and coverage

1.3 For the full sample of beneficiaries and UAs as of June 2023, we established a baseline position (looking at investment secured prior to applying for TFP), tracked investment received since in relation to both private (equity/loan) and public (innovation grants) funding. Table D-1 provides a summary of the Beauhurst coverage for both groups (Beneficiaries and UAs).

Table D-1:Summary of Beauhurst coverage

	Beneficiaries	UAs
Total number of organisations (leads and partners)	231[8]	508[9]
Number of organisations in Beauhurst database	174	268
Number of organisations tracked in Beauhurst database	85	141
Number of organisations where Beauhurst tracking has ceased	14	25

Source: SQW analysis of Beauhurst data 2023 (beauhurst.com)

Investment secured after TFP application

Private sector investment

D.3 As set out in Table D-2, most Beneficiaries and UAs did not secure equity/loan investment after the TFP application, though the proportion was higher for Beneficiaries. Compared to the baseline position, the proportion of businesses receiving private investment increased slightly for Beneficiaries (and slightly decreased for UAs).

D.4 After applying to TFP, Beneficiaries secured on average more fundraisings, and had a higher median and mean value of fundraisings than UAs. Compared to the baseline position, on average both Beneficiaries and UAs received private investment of higher value but a smaller number of fundraisings.

Table D-2: Fundraising data summary, after TFP application – Full sample

	Beneficiaries		UAs	
Overall	**N=231**	**%**	**N=508**	**%**
Organisations which secured fundraisings after their application to TFP	42	18%	60	12%
Organisations which secured fundraising after TFP application				

[8] This n figure includes one Beneficiary which is part of another beneficiary business and therefore falls under the same data in Beauhurst and is not included separately in the Beauhurst n number.
[9] This n figure includes two UAs which are part of other UA businesses and therefore fall under the same data in Beauhurst and are not included separately in the Beauhurst n number.

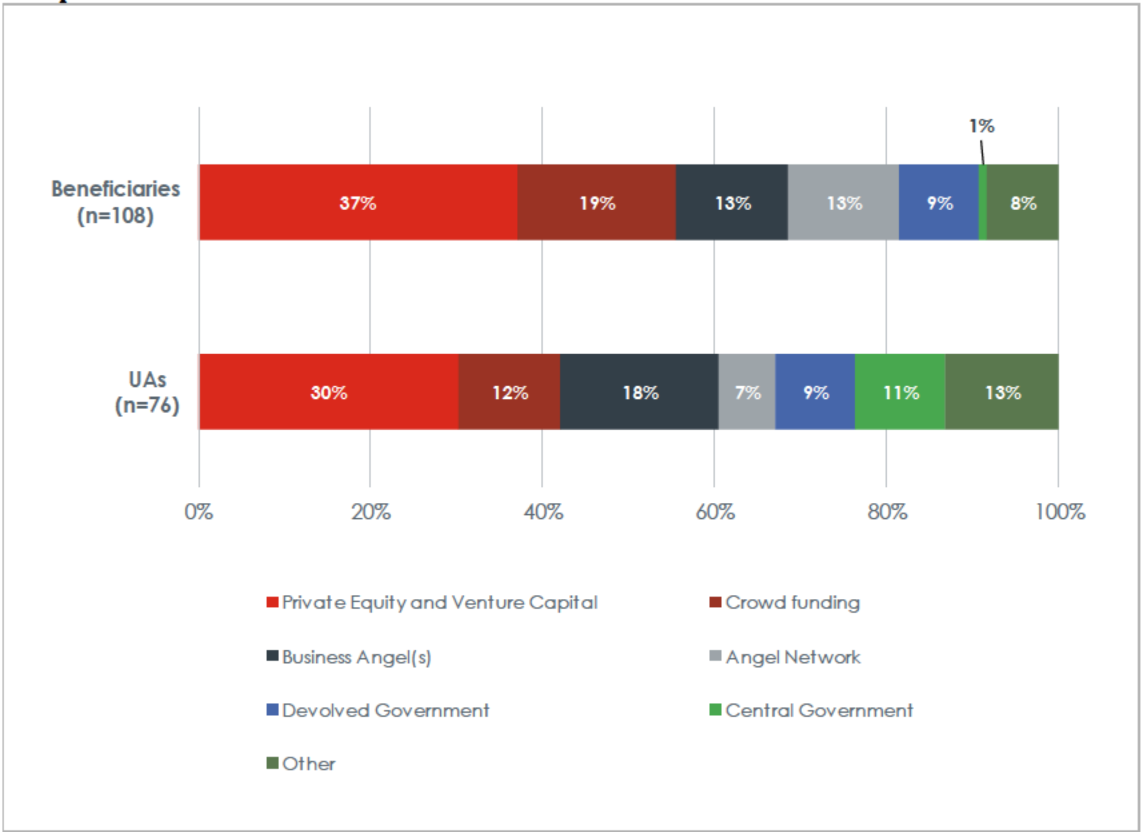
	Beneficiaries	UAs
	N=42	**N=60**
Mean number of fundraisings per business	2.5	2.0
	N=40[10]	**N=57[11]**
Median value of fundraisings (incl outliers)	£2.0m	£1.4m[12]
Mean value of fundraisings (excl outliers)	£6.2m	£3.2m
Range of fundraisings (excl outliers)	£38.1k to £35.9m	£10.4k to £24.9m
Total value of fundraisings (excl outliers)	£247.2m	£182.7m

Source: SQW analysis of Beauhurst data 2023 (beauhurst.com)

D.5 Figure D-1 presents the sources of private investment (in terms of fund types) after the TFP application. Please note the figures are based on 'deal' data (with multiple deals possible as part of one fundraising). Private equity/venture capital accounted for the biggest share of deals[13] for both Beneficiaries and UAs, though it was a relatively larger source of investment for the former. Angel networks or business angels accounted for the second biggest share (26% for Beneficiaries, 25% for UAs).

[10] N not equal to 42 as two businesses did not disclose the fundraising value.
[11] N not equal to 60 as two businesses did not disclose the fundraising value and one outlier was identified (£210.0m).
[12] N=58 as two businesses did not disclose the fundraising value.
[13] There were 108 deals with known type (source) on 57 fundraisings secured by Beneficiaries, and 76 deals with known type on 53 fundraisings secured by UAs.

Figure D-1: Sources of private investment (fund types), after TFP application – Full sample



Source: SQW analysis of Beauhurst data 2023 (beauhurst.com)

Note: 'Other' includes the following types: Corporate, University, Commercialisation Company, Management participation, Bank, Private Investment Vehicle, Local and Regional Government, and Asset Management.

D.6 In terms of investor location, the share of deals with non UK-based investors[14] was larger for Beneficiaries (28%) than UAs (22%). Similarly, follow-on investment accounted for a bigger share of deals[15] for Beneficiaries (27%) than UAs (16%).

D.7 **Public sector investment** outlines public investment[16] secured by Beneficiaries and UAs after the TFP application. The proportion of organisations which received public sector innovation grants was higher for Beneficiaries than UAs, though for both groups it was lower than their respective shares in the baseline position.

Table D-3: Grant data summary, after TFP application – Full sample

	Beneficiaries		UAs	
Overall	**N=231**	**%**	**N=508**	**%**

[14] There were 125 deals with known investor location on 61 fundraisings for Beneficiaries, and 104 deals with known location on 62 fundraisings for UAs.

[15] Based on 207 deals with on 103 fundraisings for Beneficiaries, and 198 deals on 121 fundraisings for UAs.

[16] Excluding TFP grants. Please also note that grants of over £10 million awarded to Research and Technology Organisations (RTOs) for core operations were excluded from analysis so as not to skew the distribution of funding – two such grants were excluded (both awarded to Beneficiaries).

	Beneficiaries		UAs	
Organisations which secured grants after their application to TFP	99	43%	151	30%
Organisations which secured grants after TFP application	**N=99**		**N=151**	
Mean number of grants per business		4.7		3.9
	N=97[17]		**N=148[18]**	
Median value of grant funding		£375.1k		£177.7k
Mean value of grant funding		£1.8m		£1.1m
Range of grant funding		£11.0k to £80.8m		£0.5k to £48.4m
Total value of grant funding		£176.7m		£167.1m

Source: SQW analysis of Beauhurst data 2023 (beauhurst.com)

D.8 Similarly, after the TFP application Beneficiaries secured on average more grants than UAs, but the mean number of grants per organisation was lower than in the baseline position for both groups. Moreover, the median grant value was also lower than before applying to TFP for both Beneficiaries and UAs (although in the case of Beneficiaries, the difference was marginal). However, relative to UAs, after the TFP application Beneficiaries received funding of higher value, both in terms of the mean and the median.[19]

D.9 With respect to funding sources, Innovate UK accounted for over 99% of grants[20] received after the TFP application for both Beneficiaries and UAs. The remaining grants were awarded by the Ministry of Defence and Scottish EDGE (both Beneficiaries and UAs); and the Offshore Renewable Energy (ORE) Catapult, the Advanced Propulsion Centre (APC) and Cambridgeshire & Peterborough Combined Authority (UAs only).

[17] N not equal to 99 as two organisations did not disclose the grant value.
[18] N not equal to 151 as three organisations did not disclose the grant value.
[19] It should be noted the data includes grants for non-business organisations (such as RTOs), some of which might be public sector funding awarded for day-to-day core operations. The figures should therefore be treated with caution.
[20] Based on 448 grants with known source for Beneficiaries (out of 465 grants overall), and 578 grants with known source for UAs (out of 595 grants overall).

Annex E: Technology statements

Controlled Environment Agriculture

Controlled Environment Agriculture (CEA) can be applied to a range of protected cropping systems including vertical farming (at large scale farms, in container farms or growth cabinets in restaurants and other settings), and greenhouses (including both glasshouses and polytunnels).

CEA can provide a range of sustainability and agronomic efficiency benefits including high seed germination rate, rapid crop growth, high plant density, large yields, multiple harvests per year, increased crop uniformity, and low environmental impact (with potential for low or zero carbon emissions, >90% less water usage than other systems and little, or usually no, crop protection usage). Clean crops can be produced '24/7/365' with consistent shape, size and quality, and there is less production wastage than traditional growing methods. CEA takes up less space than conventional agriculture and can be located anywhere (because soil and climate are irrelevant/less relevant, though there are important considerations in relation to the proximity of other supply chain processes, industrial/renewable energy sources and major logistics hubs). CEA is also an option for farmers looking to diversify incomes, with the potential to use existing infrastructure (e.g. former poultry sheds).[21] With a climate that is not suitable for year-round production of many crops, the UK has a particular interest in CEA and its potential to reduce reliance on imports of fresh produce with UK grown equivalents. The case for CEA has arguably become even more pressing in recent years with both Covid-19 and the Ukraine war negatively affecting food systems and highlighting vulnerabilities in supply chains and production methods. However, there have also been challenges which call into question the business model of CEA, notably the effects of increased energy costs on vertical farms and greenhouses using natural gas, rapid increases in labour and crop input costs, and the 'cost of living crisis' impacting on demand for high-value products and consumer behaviours.

Technology maturity and application

CEA covers a range of crop production systems. The focus of this summary is on CEA in the context of greenhouses (including glasshouses and polytunnels) and vertical farming. We discuss these two segments of the sector in turn for clarity, however, it is important to recognise that in practice they are closely related and should be seen on a spectrum of the level of environmental control, with shared technologies, opportunities and challenges.[22]

In terms of greenhouses, the sector is expanding and investing (largely industry led), using CEA technology to increase efficiency. Investment in new state of the art glasshouses specifically by

[21] EIT Food (2022) Barriers & opportunities for controlled environment agriculture in North-West Europe
[22] See for example Controlled Environment Agriculture - Agri-TechE (agri-tech-e.co.uk)

the commercial sector is a significant magnitude larger than investment in vertical farming (in the UK and globally), reflecting the commercial viability of this type of CEA. Under glass, CEA systems are much more mature, but still with some scope for development. For example, a range of renewable energy sources for heat and electricity are being explored (including biomass, notably wood chip, AD-CHP[23], solar energy and heat pumps), sensors are used to monitor conditions and increasingly to identify disease/pests, and leading edge LED systems are typically used (including systems that can be adjusted to provide specific frequencies to affect plant growth). Automation and robotics are also being embraced quickly as the challenges of labour supply and labour costs need to be addressed. There has also been growth in the area under glass in the UK: in the DEFRA Census the protected cropping area is shown to have increased from 2,000 ha to 3,000 ha from 2011 to 2020 after being static for 20 years previously. This included the expansion of existing growers (e.g. APS Salads, Dyson Farming, Glinwell PLC, Global Berry) and the emergence of new players (e.g. Thanet Earth, Low Carbon Farming, Greenhouse Growers, Shockingly Fresh). **Polytunnels** represent a scalable solution particularly for small-scale growers, offering more flexibility and a lower environmental footprint and lower cost option.[24]

On **vertical farming**, although some growers are quite well established with own brand produce (though with limited product ranges, primarily herbs and salad leaves) and/or sales into leading retailers, the sector is yet to demonstrate fully its commercial viability, with businesses often at the pre-profit stage, and many producers sell directly to customers rather than via retailers.[25] Growers have three choices for their technology solution: develop their own system; buy and integrate a system using components from a number of specialist suppliers; or buy a complete off-the-shelf system. The earliest growers starting out 5-10 years ago tended to develop their own systems as commercial products were not readily available, but this has changed and is now less common.

Both greenhouses and vertical farming are supported by underpinning technology solutions and providers offering a range of CEA components including: LED grow lights and associated components; growing media/substrates; supporting structures; climate control (e.g. HVAC); systems to provide water and fertigation (hydroponic or aeroponic); sensors/monitoring equipment (for temperature, humidity, CO2, nutrients, pH, crop status and condition); automation/robotics; and management software. The components need uniting into a holistic growing system, with integration technologies and systems also part of the offer from technology providers to growers. For example, growers need to use a 'recipe' for producing each crop at the different growth stages which may include: 'daylight' hours vs. 'resting' hours; intensity and wavelength of light; temperature (may be different for roots vs. shoots/leaves); air flow; % of CO2 in atmosphere; % humidity; nutrients; and pH of water/nutrient solution. In

[23] Anaerobic Digestion and micro-Combined Heat and Power
[24] UK Parliament PostNote 707 (2023) Future of Horticulture
[25] EIT Food (2022) Barriers & opportunities for controlled environment agriculture in North-West Europe

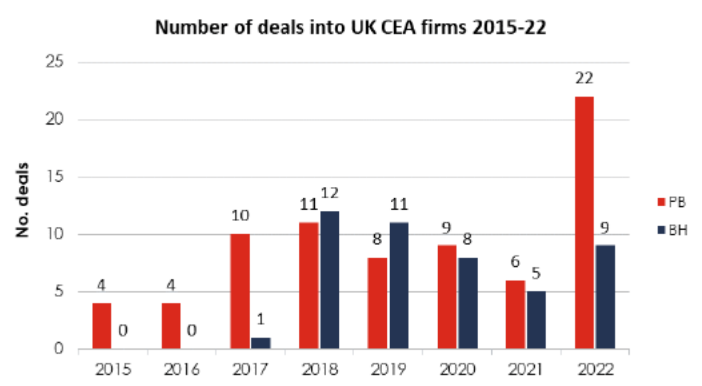
practice, there is considerable overlap across these technologies, and interoperability is likely to be important for take-up.

Some aspects of the technology are now quite well developed, but most have scope for advancement and there is potential for better integration of the different elements and for more automation/robotics. Early vertical farming growers typically produced leafy greens and herbs (especially basil). Much of the focus over recent years has gone into exploring opportunities to diversify the range of crops, for example to include soft fruits, berries and root crops, as well as the potential to grow for other markets such as food ingredients, cosmetics and pharmaceuticals.[26] For example in 2022, the Jones Food Company opened a new Innovation Centre in Bristol with the core aim of helping the firm to diversify their produce range at scale.[27] Within vertical farming, there is some evidence of pivoting with a shift away from offering the entire technological solution towards providing a part of the technology or 'vertical farming as a service'.[28]

Key recent developments and trends in the technology area

Investment

Investment is crucial for the development of CEA technologies, and the sector more widely. Figures vary by source due to challenges in accessing data on private investment, but for the latest full year (2022) Pitchbook (PB) estimates £146m of investment into UK CEA firms (via 22 deals, including one later-stage deal of £100m+) and Beauhurst (BH) provides a corresponding figure of £85m (via nine deals).[29] Pitchbook's UK investment for 2022 accounts for half of the total investment across Europe (53% of the total £276m) and one-tenth globally (11% of the £1.3bn) in this sector. Over the last five years (2018 to 2022), PB indicates an average of 11 deals per year closed by UK CEA firms (in aggregate, c. £252m via 56 deals) whereas BH suggests an average of nine deals per year (c. 129m via 45 deals).



Looking at data on the number of deals between 2015-22 shows a mixed picture (see the graph opposite). Although the latest Pitchbook data for 2022 suggests a high number of deals (relatively), over 2018 to 2021 there appears to have been a reducing trend in the number of deals across both data sources. However, it is difficult to draw any strong conclusions at this stage because year-on-year investment does tend to

[26] Agri-TechE (2023) From micro-herbs to menthol and morphine: how far will vertical farms go?
[27] Business Live (2022) Ocado-backed Jones Food Company opens innovation centre in Bristol
[28] Feedback from expert stakeholders
[29] UK companies on Pitchbook are defined as those with the HQ in the UK. On Beauhurst, this includes companies with HQ (where known, or registered address if not) in the UK.

fluctuate (reflecting the specialist nature of the area) and 2022 may reflect potentially an outlier in this general trend.

The investment into UK CEA companies has primarily come from UK funds. Among the top ten funds by value of investment, eight had UK headquarters (with others based in Luxembourg and Canada respectively).

Wider technology and market trends

Globally, the CEA market was valued at US$15.7bn in 2022, and was projected to reach US$31.1bn by 2027.[30] However, there have been some concerns for the sector in recent years. While this is partly due to economic conditions (and particularly soaring energy prices), some have claimed that vertical farming particularly is going through a market correction before it will be able to reach long-term viability[31], with some high-profile business closures both in the UK and internationally.[32] In the UK, the high energy prices are coupled with the fact that UK had historically had lower prices for fresh produce[33], making CEA less commercially attractive.

That said, there have been several large investments into and by CEA companies in the UK in recent years e.g. £100m raised by GrowUp Farm in 2022 for a new facility in Kent[34]; £42m Series B round by Intelligent Growth Solutions[35]; The Jones Food Company building the world's largest vertical farm in Gloucestershire[36]; and much of the money raised for agri-robotics focusing on CEA-type crops. This suggests a mixed picture.

Factors influencing the technology area in the UK

Commercial barriers affect the sector's ability to scale and become cost effective. There are a range of issues including: high initial costs (up to £3,000 CAPEX per square metre for vertical farms, depending on scale and system; up to £900 for glasshouses); high OPEX due to high energy requirement to power the lighting for vertical farming; and obtaining start-up funding. To generate the necessary returns on investment, vertical farm facilities need to grow high-margin produce, ideally in high volume. CEA production and logistics are complex, and learning to manage these systems effectively takes time – often longer than venture capital timelines allow for.[37] With energy and fuel prices soaring, the large energy requirement of CEA systems has become a major challenge for the sector over the past two years, especially for vertical

[30] EIT Food (2022) Barriers & opportunities for controlled environment agriculture in North-West Europe
[31] AFN (2023) Startups and scientists weigh in on future of vertical farming: "A lot of it is still a DIY hobby industry right now"; AFN (2021) Vertical farming is headed for the 'trough of disillusionment.' Here's why that's a good thing
[32] See for example here How vertical farms are weathering the climate of closure - Just Food (just-food.com) and here Lean times hit the vertical farming business - BBC News
[33] CBI (2022) The United Kingdom market potential for fresh fruit and vegetables
[34] The Grocer (2022) GrowUp Farms secures £100m in funding for vertical farm in Kent
[35] Insider (2021) IGS confirms £42 million fundraise at COP26
[36] The Jones Food Company (2021) The world's largest vertical farm
[37] AFN (2021) Vertical farming is headed for the 'trough of disillusionment.' Here's why that's a good thing

farms which have to supply all the light input and glasshouses which have used natural gas for heating (though polytunnels are much lower energy). Alongside the cost implications, balancing the high energy usage with meeting environmental sustainability ambitions and agendas can be difficult for companies. However, these challenges also present opportunities for innovation. An example of this is the world's first automated, moving conveyor system for vertical farming developed by Bedfordshire-based GrowPura, which seeks to maximise the use of space and reduce input costs.[38] There is also potential for research and innovation into heat management and transfer systems to reduce costs.

Technical barriers, which are particularly pronounced in relation to vertical farming. Key barriers include: limitations on the range of crops that can be grown and commercialised via vertical farming today; current crop varieties were not bred specifically for vertical farming (with a need for increased investment in fundamental and applied crop science research); developing optimal crop growing recipes; lack of sustainable substrates; automation and robotics. Advances in pure plant science (genomics, phenotyping, photonics, immune system priming) offer opportunities for improvements. For greenhouses, there are fewer overarching technical barriers, with well-established technologies already in place to produce a wide variety of crops, but scope for further research to leverage the full scale of opportunities (e.g. into automation, materials, coatings etc).

Skills/education barriers, with effective operation of CEA systems requiring a breadth of expertise (e.g. agronomy, engineering, data science), and a mix of education and on-the-job training. However, there is little formal education available in CEA (not covered by traditional agricultural and horticultural qualifications), and current skills provision is lagging behind commercial demand and need reflecting growing market interest. Interestingly in this context, for vertical farming specifically, many new growers come from outside agriculture/horticulture – according to the 2021 Global CEA Census, nearly half of founders (41%) had no prior agricultural experience.[39] On the one hand, this means that the vertical farming sector has benefited from harnessing the opportunity to attract younger people with a more diverse range of professional skills. However, whilst there are new skills coming into the sector (e.g. computer science), there is a risk that the more traditional skills relevant to growing crops are in a decline. In addition to the skills, a key barrier for commercialisation is a general lack of awareness among farmers, implying that demonstration of the benefits of these technologies is instrumental in adoption.[40] Increased investment in knowledge exchange, to support enhanced awareness and adoption of new technologies is also important.[41]

Infrastructure and regulatory barriers: The ability to establish growing facilities is impacted by planning permissions and land use change requirements (though this is currently being reviewed by the UK government), and there can be challenges in terms of real estate and

[38] Agri-TechE (2023) GrowPura increasing the productivity and profitability of vertical farming
[39] WayBeyond & Agritecture Consulting (2021) 2021 Global CEA Census Report
[40] Feedback from expert stakeholders.
[41] Feedback from expert stakeholders, and UK Parliament PostNote 707 (2023) Future of Horticulture

infrastructure provision in urban and rural settings respectively.[42] There are also complexities in relation to regulations, standards and support eligibility for vertical farms, though less so for polytunnels. For example, a recent House of Lords Horticultural Sector Committee report recommended that the Government should remove the 5ha limit on eligibility for Environmental Land Management Schemes MS to support urban farms, consult on business rates for vertical farming and amend the NPPF to reflect their status as agricultural businesses.[43]

Key assets and initiatives influencing UK capacity

A significant volume of relevant and high-quality plant science research takes place in the UK underpinning the development of CEA technologies. This includes research led by:

a) universities (e.g. Aberystwyth including the National Plant Phenomics Centre at IBERS, Birmingham, Bristol, Cambridge, Cranfield, Dundee, East Anglia, Glasgow, Harper Adams, Leeds, Lincoln, Newcastle, Nottingham, Nottingham Trent, Oxford, Queens Belfast, Reading, Royal Agricultural University, Sheffield, SRUC, York, Cranfield)

b) independent institutes and test beds (e.g. James Hutton Institute including the Advanced Plant Growth Centre which has next-generation controlled-environment facilities, a high-throughput phenotyping platform and vertical growth tower, John Innes Centre, Rothamsted Research, Stockbridge Technology Centre Vertical Farming Development Centre, and NIAB).

The CEA sector benefits from advances in various fields, including: automation; data analytics; energy; sensors; and materials. There is a well-developed and growing group of CEA technology providers in the UK, including those that are starting to export. Suppliers of complete CEA systems include: IGS (large scale automated hydroponic systems), LettUs Grow (aeroponic systems), Liberty Produce (container systems), Square Mile Farms (systems for canteens, restaurants etc.) and V-Farm HG (hydroponic systems). Suppliers of specialist individual components include: Airponix (aeroponic growing systems); Cambridge HOK (glasshouse and CEA structures); Light Science Technologies (LED lighting systems); Saturn Bioponics (hydroponic growth tower systems) and Vertically Urban (LED lighting systems).

Support from supermarkets is also important; a number of the UK's leading retailers are keen to take more produce from the UK and from CEA in particular (in part, as this helps in delivery against their own sustainability missions/agendas). Other relevant assets include:

Crop Health and Protection ('CHAP"), a national agritech innovation centre; activities and collaborations include:

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[42] EIT Food (2022) [Barriers & opportunities for controlled environment agriculture in North-West Europe]

[43] House of Lords Horticulture Select Committee (2023) Sowing the seeds: A blooming English horticultural sector

- The Innovation Hub for Controlled Environment Agriculture at the James Hutton Institute in Dundee (opened in 2019) carries out development, testing and research into next-generation technologies to improve the cultivation of indoor and protected crops

- The Vertical Farming Development Centre at the Stockbridge Technology Centre was set up in 2018 as a commercial demonstrator. The facility enables growers, food producers and researchers to test and develop new technologies aimed at improving all aspects of vertical farms. The Centre has hosted a range of research, e.g. on cultivating wheat indoors[44], novel aeroponic technologies[45], and non-synthetic hydrogel formulations that have the potential to reduce the carbon footprint of CEA systems.[46]

- The Advanced Glasshouse Facility at the Stockbridge Technology Centre (installed in 2017), a flexible and customisable fully-controlled glasshouse which enables bespoke testing of new plant protection products and integrated crop protection programmes. For example, the facility has provided a space for experiments on tomato varieties[47] and the fungal disease Septoria.[48]

- The Natural Light Growing Centre at University of Warwick (opened in 2019) utilising the impact of full UV spectrum natural light on crops within a protective environment. Instead of glass, the building uses ethylene tetrafluoroethylene which allows full UV penetration. The Centre reaped its first harvest of baby cucumbers in September 2020.[49]

- A joint CEA facility (CHAP, Agri-Epi and Cranfield University) at Cranfield University's main campus, which includes glasshouses, walk-in plant growth rooms and laboratory-based facilities.

- UK Urban AgriTech Collective which aims to mobilise and benefit the UK 'urban agritech community'.

- The Agri-EPI Centre, a government-funded organisation, connects researchers, startups, investors, and farmers to develop, fund, and commercialise new precision agricultural innovations.

CEA in York, North Yorkshire and Leeds has been identified as one of the UK Government's High Potential Opportunities (HPO) areas, which are selected by the Department for International Trade as opportunity areas seeking to drive investment into the UK's regions and nations.

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[44] Agronomist & Arable Farmer (2023) Is there wheat on Mars?
[45] Verticalfarm Daily (2023) UK: Aeroponic rolling benches result in uplift of 22% compared to hydroponics
[46] CPM (2023) Growing tall to nano small
[47] CHAP (2020) CHAP Advanced Glasshouse Facility enables consistency in tomato ranking trials of EU accessions; Agri-Tech E (2022) Lighting increases tomato yield by 12% – Light Science Technologies and CHAP trial finds
[48] HortiDaily (2022) CHAP carries out Septoria trials in glasshouse facility
[49] HortiDaily (2020) Natural Light Growing Centre reaps first harvest

Artificial Intelligence

Artificial intelligence (AI) - including machine learning (ML) - technologies have accelerated in recent years and their applications span most industries. These technologies remain pivotal to the success of agricultural development in the UK, where a mixture of factors and targets require significant growth in the use of data that can only be achieved by leveraging smarter data technologies.

Between increasing demand for food, more stringent environmental requirements and labour shortages, AI solutions are beginning to offer much needed advancement in agricultural capability and efficiency. As in many industries, this broad set of analysis and predictive techniques can be exploited wherever significant data volumes can be gathered and there is a spectrum of applications within agriculture, with potentially more to come. A non-exhaustive list of the areas with developing applications of AI in agriculture, and the mechanisms through which benefits may be realised, include:

- **Yield Prediction**: time-to-market; resource efficiency and waste reduction; profit; sustainability; consumer acceptance feedback.
- **Crop Monitoring:** growth, architecture and composition, morphology, phenotyping; plant breeding; precise crop maintenance and control; autonomous greenhouses/vertical farms; phenotype is driven by genetics and environmental factors; image analysis – cameras, RGB, LiDAR, 3D, Intel Realsense RGBD, moving cameras – drones, robots + software; crop advice; nutrient/fertiliser optimisation.
- **Soil, Water and Environment Management and Monitoring:** soil testing; water conductivity prediction; carbon flow modelling; decision support; crop rotation strategy; nitrogen monitoring.
- **Irrigation: sensors and microcontrollers;** soil moisture and weather prediction; smart irrigation.
- **Crop Weeding, Disease and Pest Management:** computer vision to identify and eliminate weeds/disease/pests; reduced agricultural chemical use and environmental harm.
- **Livestock: health/welfare monitoring;** health risk forecasting; behavioural analytics; reproductive performance modelling.
- **Supporting/Interfacing Robotics:** robots/drones provide the data (cameras, sensors) to carry out tasks identified by AI (kill weeds, apply pesticide/fertiliser); reinforcement learning teaches robots/drones how to act; AI could predict Return on Investment (ROI) for robot/drone investment for a particular farm.

Technology Maturity and Application

In recent years, relevant technologies and the companies offering them as solutions for agriculture have continued to evolve and mature. New start-ups have emerged, and existing businesses have grown over this period. The rapid and continuing technology progression and development, can be well demonstrated through an overview of some of the key firms operating in the area:

- **Hummingbird Technologies** – satellite and drone imaging-based machine learning analysis of geospatial and temporal trends in crop coverage, tillage, and rotation. They were founded in 2016 and underwent four rounds of funding (total £10.2m) before being acquired by Agreena in July 2022.
- **Better Origin** – AI optimised insect farming where insects are fed on food waste and the insects are then turned into sustainable animal feed. They were founded in 2015 and have raised a total of £25.8m over seven rounds and are at series A stage of funding.
- **Rezatec** – Geospatial, drone and ground-based sensors support AI solutions for crop identification, rotation planning, yield prediction/optimisation just-in-time harvesting, and supply chain optimisation. They were founded in 2012 and are a series B company after four rounds for £8.4m. They have led UK Space Agency funded projects to take remote sensing technology to Latin America.
- **Small Robot Company** – AI driven robotics for precision agriculture including monitoring, treating, and planting crops. Solutions also include an AI advice engine for suggesting optimal courses of action based on robots sensing plant level information in field. The company is at the incubator stage after eight rounds of funding (£8.4m) and was established in 2017.
- **Dogtooth Technologies** – Robotic fruit pickers that also monitor and analyse plants during growth. The robots use ML and computer vision to identify issues and predict and optimise yields. The series A company was founded in 2014 and has secured £7.8m over three rounds, two post-2021. The company had robots operating on five hectares in 2022.
- **Xihelm** – Glasshouse fruit and vegetable harvester robots that use ML and a large 3D dataset to direct its robotic arm with minimal crop damage. The robots also monitor and use ML models to harvest at optimum ripeness. Xihelm seek to address adoption issues with expensive robotic equipment by offering Robotics as a Service (RaaS). The venture capital stage company was founded in 2016 and most recently received additional funding in 2020.
- **Muddy Machines** – Robotic harvesters using deep learning and reinforcement learning for automated control and harvesting crops at optimal maturity. The onboard sensors also gather data and use ML to forecast yield. The incubator stage company was founded in 2020

and has generated £1.6m in funding over eight rounds, most recently in 2022. They describe their offerings as 'farming-as-a-service.'

- **Antobot –** This company offers a series of AI driven robots that perform crop monitoring and yield prediction as well as logistics support. Antobot address some barriers to adoption by supplying their own farm mapping and wireless network as well as apps and a web portal to feedback to the user. They also assure that while data is fed to their deep learning model, the ownership remains with the farmer. The incubator stage company was founded in 2016 and was most recently funded in 2022.

- **Cattle Eye –** AI driven video analysis for health monitoring in cattle. The solution is largely software based with an accompanying app for reporting insights. It relies only on low-cost security cameras for data. The seed venture capital stage company was founded in 2019 and has raised £2m over four rounds. The solution is currently deployed on 38 farms.

- **Mantle Labs –** Deep learning analysis of near-real-time satellite imagery of the Earth. Products target both farmers and portfolio managers/insurers by estimating crop coverage and health. The incubator stage company was founded in 2016 and has received one round of funding.

- **SAGA Robotics** - Established in the UK (Lincoln) in 2016 as a spinout from a Norwegian University. With the support of the University of Lincoln, UKRI and two major funding rounds in the last four years (raising over £16m), it now has commercial robots in five countries globally and has grown from three staff in 2016 to over 50 currently. It has commercial applications, such as UVC treatment for powdery mildew which are offered as a robot as a service model.

- **Fruitcast** - Lincoln University spinout using AI and ML to estimate crop yields. FruitCast secured £2.8m in a recent funding round as it continues to expand and develop its technology, and investment from CERES AgriTech. FruitCast's technology relies on AI-enabled data analytics and yield forecasting, offering precise predictions for labour and market planning up to six weeks in advance. The service aims to help growers optimise their operations and increase profit margins while reducing waste.

- **Agaricus Robots –** A Spinout from the University of Lincoln, supported by CERES AgriTech. It is developing mushroom harvesting robots and has trials in place with one of the UK's largest mushroom producers.

- **Peacock Technology –** Founded in 2008, Peacock is an advanced engineering and robotic automation company specialising in machine vision and artificial intelligence for use in the dairy industry.

As suggested from the (non-exhaustive) list above, AI technologies applied in agriculture can be broadly grouped into 'robotics and automation', 'satellite imagery analysis', and 'AI analytics to support animal husbandry' categories. Broadly, AI driven robotics appears to be the area that has developed most fully in recent years. A key driver for innovation in the use of AI in robotics is the growing interest in high tech greenhouses and vertical farming, where the carefully controlled environments reduce some of the traditional challenges of robotics such as uneven terrain.

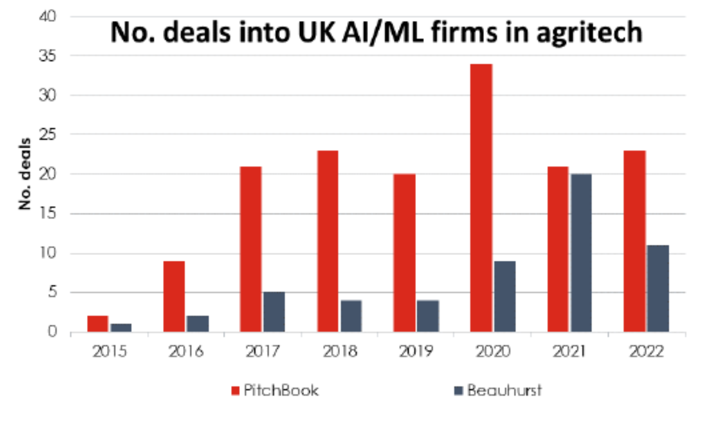
A key advantage of robotics is that not only does ML help to drive the robot to perform a task like picking, but the robot can also be harvesting rich datasets through multiple onboard sensors. This constitutes an opportunity for one technology to be used to both automate a task and provide predictive analytics and decision support by analysing the data it gathers. While the investment required may be higher, a robot in a field can provide most of the analytics potential of a satellite view of that field but with added functionality. The use of ground truthing using a robot can allow satellite, drone and UAV data analytic systems to be trained, in turn allowing much larger areas to be covered more frequently than could be achieved with a ground-based robot. The development of multi-layered sensing systems are being applied to arable crops and use cases such as forestry management.

Robotic technologies have demonstrated a growing exploitation of multifunctional capabilities in agritech but there remains a largely untended gap in the market for holistic 'whole farm' integrated technologies than can provide analytics and decision support based on multiple systems. Given high costs and issues around data standards and interoperability, these integrated offerings may not currently be commercially attractive, but ultimately if a farm were to exploit several systems like robotics and satellite/drone data to maximum effect then a unified control centre that could marry these technologies would be required. Data Trust when sharing data between users and applications is also a key area of research which has been explored by projects such as the Internet of Food Things Network[50]. At EU level, the agricultural machinery manufacturer association CEMA, worked with the European Commission in 2018 to develop a Code of Practice on data sharing, to both clarify that farmers own their own data and to encourage common data standards so the data from multiple machinery suppliers can be shared.[51]

[50] See foodchain.ac.uk
[51] CEMA: European Agricultural Machinery EU Code of Conduct on agricultural data sharing (cema-agri.org)

Key recent developments and trends in the technology area

Investment



As shown in the figure opposite, UK agritech firms with a focus on AI have seen a rise in the number of deals secured over the 2015 to 2022 period. The graph draws on both Pitchbook and Beauhurst investment data and suggests there has been growing interest in this area from the investment community. Both Pitchbook and Beauhurst suggest c.£25-30m investment into agritech firms with a focus on AI in 2022.

Wider technology and market trends

A key trend in agritech is the increased adoption of automation technologies, with many manufacturers exploiting existing and trusted models of farm equipment by adding in new intelligent features. Popular tractor models, such as Kubota's L series, are being enhanced with additional AI and data driven technologies such as crop mapping and automated steering.[52] Israeli and US based Blue White Robotics are building autonomous steering and control systems which can be added to multiple makes of tractors and farm machinery.[53] Alongside enhancing existing models, many manufacturers are also producing early concepts and prototypes for fully autonomous farm equipment, such as John Deere who have demoed a range of new technologies such as driverless electric tractors and drone sprayers.[54] Globally the agritech robotics market is projected to reach $8.82B by 2025 at a compound annual growth rate of 24.7%, with much of this potential underpinned by AI technologies. So far, this growth has been concentrated in the US and Asia but there is evidence of growing, if slower, uptake in Europe and the UK.[55]

An emerging but immature trend that is borrowed from other industries like manufacturing, is the use of 'digital twins' to simulate a farm and its assets. One way in which these models can be exploited with AI is through reinforcement learning (RL) where artificial agents are trained to make farm management decisions within the simulated environment and incrementally improve their behaviour to optimise some reward such as crop output. This approach can often expose novel strategies that humans may not be aware of, but the process relies on realistic simulation and hence a high-fidelity digital twin.[56] An example of a digital twin project is the North Wyke Farm Platform, developed by Rothamsted Research. In collaboration with the Alan Turing Institute, Rothamsted has recently been awarded funding to further develop the platform.[57]

More widely, the past two years has seen significant advancements in AI technologies, notably the commercialisation and widespread adoption of large language models (LLMs) has begun to transform many industries. These models have started to impact other industries such as software development, and while they remain immature in the context of agriculture, they represent a significant opportunity.

For example, Open AI's Chat GPT has proven to the world the myriad ways in which these models can revolutionise ways of working. A common application is to use chat-bots to facilitate efficient business-customer interaction, but within farming there is also scope for querying technical documents.[58] Farms need to maintain an increasing range of technology and the corresponding maintenance and operation literature will start to become challenging to manage. LLMs can help to address this by allowing human readable querying, not only of technical documents but also knowledge shared between farmers on forums. An academic paper from June 2023 details the development of 'AgriBERT', a language model trained on food-related text to establish mappings between food descriptions and nutritional content.[59] While farmers could potentially use Chat GPT to answer agricultural queries, a dedicated agriculturally trained model is likely to provide much more useful and reliable results.

Further, there is potential for an agriculturally trained model like AgriBERT to be sold as a product that could be 'finetuned' on farm data such as reports and manuals for machinery. These bespoke models could answer queries particular to the farm and provide unique benefits. This approach is being explored in other industries and helps to address data privacy concerns, as the model could be hosted locally. Fruitcast, based in Lincoln, is beginning to use LLMs to manage large datasets for crop forecasting.

A trend in ML is the growing interest and capability in making powerful models small and efficient enough to run on edge devices, potentially allowing advanced ML to be incorporated into farming equipment and reducing reliance on cloud technologies potentially inhibited by poor internet in rural areas.

Another key development is the rise of federated learning, whereby a centralised model is trained on the outputs of many underlying models, each with their own private dataset. These underlying models could be deployed on edge devices like smartphones or robotics and allow exploitation of vast collaborative datasets without any individual party actually sharing their

[52] Kubota Group (2022) The Labour Saver
[53] https://www.bluewhite.co/
[54] John Deere (n.d.) Future of Farming
[55] European Parliamentary Research Service (2023) Artificial Intelligence in the Agri-Food Sector: Applications Risks and Impacts.
[56] Verdouw, C. (2021) Digital Twins in smart Farming.
[57] Rothamsted News: Rothamsted to collaborate with new £3m digital twin research network
[58] Gamulin, N. (2023). GrainBrain: Harnessing AI and Large Language Models for Agricultural Science.
[59] Saed Rezayi, Z. L. (2023). Exploring New Frontiers in Agricultural NLP: Investigating the Potential of Large Language Models for Food Applications.

data. This serves to both reduce barriers around data privacy and also support training of very powerful centralised models with diverse inputs.[60]

Factors influencing the technology areas in the UK

A number of factors and barriers are evident that influence and may prevent the exploitation of AI technologies in agriculture. Key factors/barriers include:

- **Technology familiarity**: many farmers remain largely unfamiliar with AI technologies, with one survey of UK farmers indicating that 55% of respondents had no immediate plans to invest in advanced agritech technologies including AI.[61] Those that are familiar still may face barriers in communicating with AI engineers. However, there is an onus on tech firms to frame AI technologies in a way that relates to the everyday needs of farmers, and technology providers need to prioritise articulating the potential practical uses and commercial value of the technologies, rather than underpinning technical detail.[62]

- **Data access**: a primary concern for many farmers is trust about how their data is used, amplified by increasing awareness of the risks associated with data privacy and AI. Farmers need confidence that their commercially sensitive data remains under their ownership and is not vulnerable to misuse, intentional or not (data breaches and hacking or issues like large language models generating copyrighted content).[63] Some AI agritech solution providers are recognising the trust issues around data sharing and are offering assurances of the farmer retaining data ownership, as well as developing solutions where the data does not have to leave the farm. On the ground experience suggests that when farmers are well informed as to how their data will be used, there is rarely an issue in sharing data.[64] The British Farm Data Council has been established with the aim of improving transparency around how data is used. The accreditation has been endorsed by the NFU and other industry bodies.[65]

- **Data availability**: The availability of data is one of the key enabling factors for the development of AI technologies, due to the role of data in benchmarking and training AI. In agriculture, data quality and coverage can be an issue and data collection is often focused on compliance (e.g. related to regulation requirements). Expert stakeholders reported that in their experience there has not been a material upward trend in the quantity or quality of data captured on the average farm in the past 10 years. In some cases, data availability issues are being solved by AI solutions either gathering or providing the data themselves, through the use of robots with sensors, and satellite analysis products relying on existing data sources.

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[60] Ibid.
[61] Barclays. (2021). Insight to AI in UK Agritech
[62] Feedback from expert stakeholders.
[63] Priest, A. (2023). Farm smarter, not harder – who owns the data generated from smart farming?
[64] Feedback from expert stakeholders.
[65] The British Farm Data Council

- **Data standards**: lack of standard data formats and interoperability limits the adoption and development of some technologies.[66] While many farm vehicles collect useful data from numerous sensors, there is little uniformity across different manufacturer/equipment. This can slow down the development of AI solutions as it presents greater challenges in preparing and handling disparate data sources before they can be used. Reduced interoperability of these technologies prevents full exploitation which can be gained through systems integration. Data standards remains an issue and will be difficult to solve, especially as the rapidly growing suite of AI applications will continually evolve new data requirements. This is not an issue for some technologies that are self-contained and gather their own data, but does still limit and complicate the simultaneous exploitation of multiple systems. The CEMA Code of Practice on Agricultural Data Sharing (2018) sought to respond to this issue, and a similar development is being proposed in the USA. The Data Driven Decisions for Dairy Farmers (4D4F) project led by UK based Innovation for Agriculture and funded by Horizon 2020 tackled the issues of data integration in the dairy sector by combining data from multiple sensors.[67] Semantic web technologies are also being used to address data integration issues. Indeed, knowledge graphs (which use semantic technologies) complement machine learning techniques to: reduce the need for large labelled datasets; facilitate transfer learning; and encode domain, task and application knowledge that would be costly to learn from data alone.[68]

- **Infrastructure:** AI solutions rely on data, and in many cases require low latency to provide accurate and timely insights. This data must be passed between vehicles/robots, satellites, cloud/datacentres, and edge devices such as smart phones/tablets. This can be a challenge in rural areas due to poor internet and 4G/5G coverage. The UK landmass coverage of 4G has been growing very slowly in recent years, plateauing at 91% in 2019 but projected to reach 95% by 2025 driven by Government's Shared Rural Network (SRN) agreement. Rural coverage for 5G is likely to take significantly longer which may inhibit deployment of larger more advanced AI models and reduce the capability of farms to field multiple AI solutions at once. Infrastructure is likely to be a persistent but evolving barrier, the SRN agreement is addressing 4G coverage but 'levelling up' 5G targets only describe 'a majority of the population will have access to a 5G signal' by 2030. This coverage is likely to be front-loaded on urban populations before making its way to rural areas and while more can be done with AI solutions under current infrastructure, this may affect the development of next generation solutions with increased data requirements.

There are initiatives that seek to support enhanced connectivity in rural areas such as '5G RuralFirst' who partner with AgriEPICentre to develop and demonstrate 5G testbeds and associated technologies in remote locations.[69] LIAT at the University of Lincoln installed the UK's first 5G private network for agriculture in 2021 at their Riseholme farm and have also worked with food logistics companies on the use of 5G for real time data interchange in the

[66] Dowling, J. (n.d.). What's in the Way? Removing Barriers to the Agri-Food Data Revolution.
[67] See: 4D4F (n.d.) Data Driven Dairy Decisions for Farmers
[68] Alan Turing Institute (n.d.) Knowledge Graphs
[69] AgriEPICentre (n.d.) Wireless and mobile connectivity with 5G RuralFirst

post farm food chain. Norfolk County Council with partners created a 5G testbed in North Norfolk in 2023, an area dominated by tourism and agriculture, with use cases in both sectors now being explored.

Return on Investment: farmers remain concerned about the significant start-up costs, uncertain timeframes, and value for return on their investment in AI enabled technologies. Return on investment is a persistent barrier with any new technology, although the growing number of cases where these new technologies have been applied successfully can help to mitigate these concerns. Many of the companies offering these solutions communicate the number of farms that have deployed their technologies. Technology demonstrators such as the Hands-Free Farm (previously Hands-Free Hectare) continue to evolve and provide farmers with evidence of the benefits of automation.

Return on Investment is also a challenge for companies developing AI technology. Creating meaningful models often requires data from thousands of farms, and collecting this data can be a time consuming and costly process. AI companies therefore often require large investment sums at a reasonably early stage which presents a challenging RoI position for investors given barriers to scaling and exporting.

Internationalisation: agri-focused AI presents particular challenges in relating to export potential, owing to the source of the data it is trained on e.g. AI trained on data from UK farms may not be appropriate for application elsewhere. Issues around exportability combined with other barriers to growth (such as availability of finance) means it is sometimes difficult for AI businesses to scale in the UK. There are several examples of AI firms which have struggled to get traction in the UK market and have, as a result, moved overseas or been acquired by foreign firms. This includes Hummingbird Technologies (acquired by the Danish firm Agreena) and Breedr (relocated to the US).

Key assets and initiatives influencing UK capacity

The UK is world leader in AI research: the UK is ranked third globally for the percentage of AI leaders, and London is considered 'Europe's AI Capital'.[70] This strength is underpinned by the UK's broader research expertise in computer science and informatics, and mathematics. Key centres of research excellence and scale (as identified in the REF 2021) in computer science and informatics include Imperial College London, University of Oxford, University of Birmingham, UCL, and University of Edinburgh.[71] Other centres of excellence in AI identified in a recent review of the UK's AI landscape include the University of Southampton, University of St. Andrews, University of Bristol, University of Leeds, University of Surrey, Durham University, and the University of Glasgow. [72]

[70] Digital Catapult (2021) UK-Netherlands & Artificial Intelligence: Policies, trends and opportunities for bilateral collaboration.
[71] Times Higher Education (2021) Computer Science and Informatics
[72] Digital Catapult (2021) UK-Netherlands & Artificial Intelligence: Policies, trends and opportunities for bilateral collaboration.

On AI specifically, there is a network of research assets across the UK in universities including the Leverhulme Centre for the Future of Intelligence (an interdisciplinary research centre addressing the challenges and opportunities posed by AI based at the University of Cambridge, with partners at Imperial College London, University of Oxford and UC Berkeley), the Data Science Institute at Imperial College London, UCL Centre for Artificial Intelligence, and the University of Manchester's Institute for Data Science and Artificial Intelligence. Further, UKRI invested £100m in 2018 to support the establishment of 14 Centres for Doctoral Training (CDTs) in AI to train the next generation of researchers, and in 2023 announced a further £117m to continue training doctoral researchers in AI across the remit of UKRI from 2024/25 academic year. This includes the establishment SUSTAIN, led by the University of Lincoln (working with the University of Aberdeen, Queen's University Belfast and University of Strathclyde) focused on the application of AI in agri-food. It will cover technical and social science aspects of AI, alongside training in plant, animal and/or biosciences.[73]

Other key AI assets include the Alan Turing Institute, a research collaboration between thirteen leading UK universities alongside the EPSRC. The institute has an ongoing project to construct a national scale integrated crop modelling framework, seeking to incorporate numerous data streams to investigate future crop strategies that are robust to threats from climate change.[74]

The UK also has dedicated institutions targeting the future development of food production working in AI such as Harper Adams University who have recently been collaborating with the University of Newcastle to apply AI video analysis for monitoring dairy cow health, amongst many other projects. The Lincoln Institute of AgriFood Technology (LIAT) has multiple projects working on digital agriculture, with a parallel training programme with a 50 PhD CDT, AgriForwards, and MSc courses in agritech and data analytics which are now attracting over 200 students per annum. The LIAT work closely with Cambridge Enterprise on CERES agritech to create economic impact from this work. The Agri-EPI Centre also worked widely in AI, including brokering industry and academic collaboration in agritech, and facilitating commercial trials with investors, growers and researchers.[75] Rothamsted Research also has AI-related strengths/assets include around semantic web technologies and digital twin technologies.

Related to this, the UK also has a strong network of agri-food research institutions with significant historic datasets from long-term experiments and breeding programmes which can be used to inform and train AI models and technologies. This includes experiments/programmes managed by dedicated research institutions, such as the Centre of Ecology and Hydrology, James Hutton Institute, Rothamsted Research, and IBERS. Other important sources of data include the Agriculture and Horticulture Development Board (AHDB) and the Farm Business Survey, and Hestia, run by the Oxford Martin School at the

[73] University Secures UKRI Funding for Transformative Centre for Doctoral Training | News and Press (lincoln.ac.uk)
[74] Alan Turing Institute (n.d.) The impact of climate change on agriculture
[75] Robotics, AI and Automation - Agri-EPI Centre - Agritech Innovation

University of Oxford[76] which provides an open-access platform that stores standardised data on agricultural production.

In terms of key initiatives, the new Bridge AI programme was launched in 2023. It is a £100m investment by UKRI targeted at four sectors, one of which is agriculture.[77] The programme aims to harness the power of AI and support businesses to unlock their full potential through providing funding and support to help innovators assess and implement trusted AI solutions, connect with AI experts, and elevate their AI leadership skills. The UK Government also recently announced £31m to create a UK and international research and innovation ecosystem for responsible and trustworthy AI. The consortium is led by the University of Southampton and will fund multi-disciplinary research and work across academia, business, and the public sector.[78]

Robotics

Robots are machines which can substitute for human actions, often utilising the outputs of AI and data analytics to perform repetitive tasks. In growing and harvesting, a huge variety of robots are currently in different stages of development or early deployment, from 'picking robots' which selectively pick only ripe fruit, to self-driving tractors, to robots capable of precision weed killing.

Agritech robots need to be highly specialised as the complexity of the robotics required, the type of robot needed, and the potential gains from automating all vary by purpose and crop. The field of robotics in growing and harvesting is characterised by continuing technological and commercial development at pace, although workshop attendees reported challenges relating to investment.

Technology maturity and application

Whilst more complex robotic solutions – including 'autonomous selective harvesting' involving mobile robots autonomously navigating the growing environment, inspecting, harvesting and transporting crops – are still in the early stages of R&D and are unlikely to be fully rolled out before 2030[79,80], other robots are in field tests and near (and in some cases at)

[76] Achieve more sustainable agriculture | Hestia
[77] See: KTN (2023) BridgeAI: Driving Business Productivity with Artificial Intelligence Workshops
[78] £54 million boost to develop secure and trustworthy AI research - GOV.UK (www.gov.uk)
[79] Department for Environment, Food & Rural Affairs (2022). *Automation in horticulture review*. Available at: https://www.gov.uk/government/publications/defra-led-review-of-automation-in-horticulture/automation-in-horticulture-review
[80] David Christian Rose, Mondira Bhattacharya, Adoption of autonomous robots in the soft fruit sector: Grower perspectives in the UK, *Smart Agricultural Technology*, Volume 3, 2023. Available at: Adoption of autonomous robots in the soft fruit sector: Grower perspectives in the UK - ScienceDirect

commercialisation. Many firms are developing multiple robots in parallel, with a forerunner nearing commercialisation and others still in early-stage R&D. Overall, the commercial use of robots in growing and harvesting remains fairly small scale at present, and is likely to start to have a significant impact on farming practices more widely in the next few years.[81] For now, the key challenge for most early movers is to offer a cost competitive solution, relative to existing methods.

In general, as may be expected given the practical challenges, the more complex robotics technologies which have the potential to offer the greatest benefits in terms of efficiencies and labour savings (i.e. autonomous selective harvesting) appear to be the furthest from commercialisation. Some crops also offer more potential for automation than others, with robotics for high value crops likely to achieve cost parity with existing methods sooner, and some crops proving less technically challenging.

Robots are likely to be adopted on large, industrialised farms, where production is more standardised and the scale of operations can more easily justify the cost of robotics. However, there is also many opportunities for small farms (with no or few employees) to introduce robots to relieve workload. In the dairy industry, for example, the uptake of robotic milking technology on small farms has been strong as it allows farmers to take holidays and work more flexibly. The same is likely to be true in robots for growing and harvesting.

Robots have significant potential to offer efficiency savings in crop picking and these technologies are advancing quickly. Currently, prototypes can pick strawberries, raspberries, lettuce, mushrooms, broccoli and asparagus, and some harvesters are already commercially available. Whilst simple for humans, these dexterous tasks are complex for a robot, requiring them to identify ripe fruit and pick it without damage to produce or plant. A number of firms have developed working prototypes, with some currently carrying out field trials and a minority beginning to commercialise (e.g., Saga Robotics, Muddy Machines, Fieldwork Robotics, UPP and RoboVeg broccoli harvesting). There are some companies providing "robotics as a service" model in harvesting, including Tortuga. Robots are also being developed to transport fruit to and from pickers, e.g. Antobot's Assist robot is being tested on UK farms, Saga robots are being trialled in fleets to perform this function, and G's Growers are using a robot to move young plants around their greenhouse nursery in Cambridgeshire, as are Hillgate Nurseries in Norfolk.

Robots also have strong potential in precision weeding, and this is an area which has advanced significantly in the past five years. Instead of spraying an entire field with pesticides etc., using AI, robots can target treatments at individual plants, offering significant savings on chemical usage and reducing spraying time. Weeding robots may also use non-chemical methods, such as automated hoeing. This area has experienced significant investor interest, with Earth Rover and the Small Robot Company examples of firms leading the way in the UK. Saga robots have also been using UVC treatment powered by their robot platform to treat soft fruit crops for

[81] Inews (2023). *How robot pickers are being used to tackle farmers' Brexit woes – but are not as fast as humans.* Available at: https://inews.co.uk/news/robot-pickers-answer-farmers-brexit-2351571

powdery mildew, with the first commercial scale trials in the UK in 2021 and 2022, now leading to this service being sold internationally. This is a good example of robots as a service, with crop care paid per metre of crop bed, which reduces farm investment and enables a full service to be provided.

The emergent UK viticulture sector is also looking to use robots developed in Europe for crop care to enable it to rapidly scale its crop area as climate change leads to opportunities for expansion in the domestic vineyard sector.

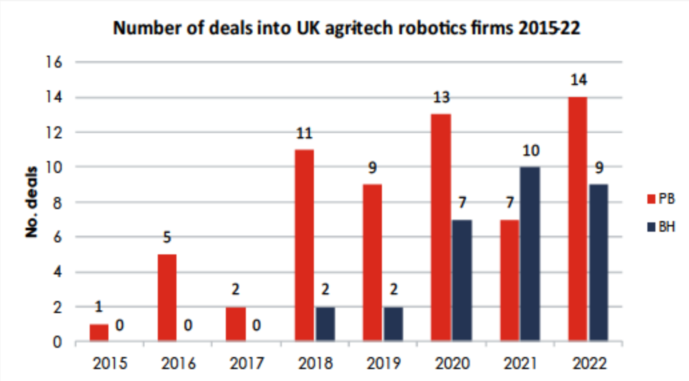
Whilst many of the companies mentioned above are focused on relatively small robotic technologies, there are some companies developing large robots as well. This includes AGExceed which has recently started demoing large tracked machines in the UK.[82]

Key recent developments and trends in the technology area

Investment

In the latest full year (2022) Pitchbook (PB) estimates £17.4m was invested in agritech and robotics firms via 14 deals, whilst Beauhurst (BH) estimates a slightly lower figure of £11.9m via 9 deals (the data covers firms with their HQ in the UK).[83] For context, PB data indicate investment in UK agritech robotics firms equated to 15% of the total investment across Europe (£110m) in 2022 and 5% of globally (£360m) in this space. Over 2018-2022, PB indicate there were on average 11 investments per year into UK agritech robotics firms (in aggregate, c.£51m via 54 deals), with BH indicating on average 6 deals per year (in aggregate, c.£26.5m via 30 deals).

Looking over the longer-term from 2015-2022, there is no consistent pattern in the annual *value* of deals across PB and BH data, with significant year-on-year fluctuations. This reflects the specialist nature of the area, and impacts of single large investments. However, as shown in the graph opposite, the data on the *number* of deals does suggest a growing interest in the area amongst investors overall; this positive trajectory is seen in both data sources. This picture is supported and complemented by qualitative sources of evidence and commentary e.g. reports of investment 'pouring' into weed zapping robots.[84]



[82] AgXeed | We provide autonomy
[83] Figures vary by source given challenges in accessing data on private investment
[84] Inews (2023). *How robot pickers are being used to tackle farmers' Brexit woes – but are not as fast as humans.* Available at: https://inews.co.uk/news/robot-pickers-answer-farmers-brexit-2351571

Conversely, industry stakeholders engaged with as part of the tech tracing process reflected that the amount of private investment in robotics is not sufficient. In particular, robotics companies face a challenge securing funding from the later Technology Readiness Levels through to scale up (i.e. bridging the 'valley of death'). There are mixed views around the effectiveness of public sector support at earlier stages. For example, the match funding/co-investment element of grant support in the UK is challenging for some SMEs in robotics where large investment is required given the hardware intensive nature of these projects. Relatedly, stakeholders highlighted that early-stage investment in the UK is often significantly less than companies typically secure in other countries (e.g. the US). This results in a somewhat fragmented landscape where a lot of smaller projects are progressing.

Key investors since 2015 into UK agritech robotics include Regenerative Ventures and Elbow Beach Capital, which are UK based. Garford Farm Machinery was majority acquired by large German agricultural machinery manufacturer, Zurn Harvesters, in 2019. Crowdcube was responsible for the greatest number of fundraisings (5), potentially reflecting crowdsourced investment from farmers. The Small Robot Company alone reports nearly 500 farmer investors, demonstrating strong demand within the sector.[85]

Note: the data above focused on firms with an HQ in the UK. This excludes Saga Robotics, which has an HQ in Norway but its main team in Lincolnshire since 2016 and has secured nearly £20m in two funding rounds in 2020 and 2022; the latter included £8.5m to fund growth within the strawberry sector in the UK.[86]

Wider technology and market trends

Identifying developments in the technology in recent years is challenging given this remains an area with few market players: for example, Beauhurst (which tracks high-growth UK firms) identifies nine firms working in robotics in the agriculture sector, but this is believed to underplay the sector, with desk-based research suggesting there may be as many as 20 established firms in the sector operating in the UK.[87] Little information is available online (given commercial confidence) and developments for individual firms can significantly influence overall trends.

However, the available evidence suggests that firms have continued to advance their technology, and that the UK overall has developed and enhanced its potential to play a leading role in this field over the long-term.[88] Notably, a handful of firms are commercialising their most developed robots whilst, alongside a wider pool of market players, they continue to develop earlier stage robots with public sector support for R&D investment. In this context,

[85] The 4AR (2023). *Robots look to make their mark*. Available at: https://www.the4ar.com/4ar/robots-look-to-make-their-mark
[86] Saga Robotics raises £8.5M to fund UK growth for strawberries - Thorvald - Saga Robotics
[87] Saga Robotics, Antobot, Fieldworks Robotics, Muddy Machines, Saga, E-Nano, Crover, Lisst IO, Earth Rover, Agaricus, Roboveg, Fox Robotics, Robotriks, Dogtooth Technologies, UPP, Garford, Autopikr, Growpura, Rickerby Estates
[88] Crop Health and Protection Limited (CHAP) (nd). *How can robotics and automation revolutionise the CEA sector?* Available at: How can robotics and automation revolutionise the CEA sector? - CHAP (chap-solutions.co.uk)

the review of available information suggests that agritech robotic firms are focussed on reducing production costs and speeding up robot functionality to achieve cost effectiveness compared to existing solutions.

Examples of key developments since 2021 include:

- The Small Robot Company made its first commercial sale of one of its robots (Tom v4) to the National Robotarium in June 2023. Tom V4 is capable of remotely scanning fields to identify weeds and crop plants, using AI to tell farmers how much herbicide to use and where. The firm also successfully completed trials of its Per Plant Farming Service, whereby farmers subscribe to share a robot as part of a group of six. According to the firm, demand is high with over 140 farmers waiting for the service[89]. The firm was also recently awarded £2.6m by Defra's Farming Innovation Programme to develop slug control robot technology[90].

- Fieldwork Robotics, a University of Plymouth spin-off has commercially deployed their raspberry picking robot at two locations in Portugal. The firm is now working to speed up the picking process, whilst driving down production costs.[91] Following continuing successful field trials in Portugal, Fieldwork Robotics secured £1.5m in investment from Elbow Beach Capital in August 2023, as part of a wider venture capital round.[92]

- Antobot continue to develop their AI powered robots, with ongoing public funding across several research projects, including TFP funding for its crop scouting robot, Insight.

- Muddy Machines' Sprout robot is picking asparagus in fields. The prototype is slow but has strong potential; asparagus is well-suited to robotic harvesting, as a simple plant (one spear) which can grow very fast. Following significant public investment, Muddy Machines secured seed funding of £1.5m in 2022, allowing them to develop a herd of robots for the 2023 asparagus season and hopefully begin to generate revenues.[93]

- Norwegian firm, Saga Robotics, raised £8.5m in private investment in October 2022 (and €10m in 2020) primarily to accelerate their growth in the UK strawberry sector after

89 The 4AR (2023). *Robots look to make their mark*. Available at: https://www.the4ar.com/4ar/robots-look-to-make-their-mark
90 The Small Robot Company (2023). *£2.6m Defra-funded project launched to revolutionise slug control*. Available at: https://www.smallrobotcompany.com/press-releases/2023/6/29/26m-defra-funded-project-launched-to-revolutionise-slug-control
91 University of Plymouth (2022). *Company makes significant progress with raspberry harvesting robots*. Available at: https://www.plymouth.ac.uk/news/company-makes-significant-progress-with-raspberry-harvesting-robots
92 The Times (2023). *Fieldwork Robotics unjams shortage of fruit pickers with AI raspberry harvester*. Available at: https://www.thetimes.co.uk/article/fieldwork-robotics-unjams-shortage-of-fruit-pickers-with-ai-raspberry-harvester-99wtbjx53
93 Muddy Machines (2022). *Muddy Machines secures £1.5m to develop next-generation crop harvesting robots*. Available at: https://www.muddymachines.com/post/muddy-machines-secures-1-5m-seed-round-led-by-regenerate-ventures

basing their R&D team in Lincoln from 2016[94]. Their robot recently covered more than 30 hectares of strawberries in plastic tunnels at Clock House Farm in Kent.

Factors influencing the technology areas in the UK

There are powerful external drivers pushing the pace of innovation in robotics in growing and harvesting, encouraging both public and private investment and accelerating technology development.

Globally, **farmers are under increasing cost pressure**. Since 2021, low profit margins have been further strained by the outbreak of war in Ukraine, which has pushed up agricultural input prices: fertiliser prices more than doubled from summer 2020 to summer 2022.[95] Extreme weather is also impacting crops globally (summer 2022 was one of the driest on record in the UK[96]), and extreme weather events are set to become more regular as the climate crisis worsens. Meanwhile, in the UK, farmers are under pressure to keep prices low as consumers struggle in the cost-of-living crisis. EU Exit also continues to impact UK farming specifically, as farms struggle to find seasonal workers. It has been estimated that up to £60m of food was left to rot in fields in 2022[97], as a direct result of labour shortages.

Since early 2016 the introduction of the National Living Wage (NLW) means that the wage costs for those paid the old minimum wage, now the NLW, have risen from £6.19 per hour in January 2016 to £10.80 in 2023, a 75% rise in 7 years (before accounting for inflation), with further rises expected. With labour costs representing over a third of the total costs of production for many intensive crops, this wage cost pressure is incentivising the use of robotics and automation.

These factors are accelerating a push for innovation as start-ups, farmers and government recognise the potential for labour saving robotics technologies to alleviate these challenges. A recent UK survey found that 76% of soft fruit growers believe that autonomous robots are the future of the UK soft fruit industry and **labour shortages are the major driver for technology adoption.**[98] Importantly these trends are not unique to the UK, but increasingly a global issue. Robots have the potential to replace human labour, drastically lowering wage costs to farmers. Higher input costs also make robotic technologies relatively more cost effective e.g. reducing

[94] Saga Robotics (2022). *Saga Robotics raises £8.5m to fund UK growth for strawberries*. Available at: https://sagarobotics.com/saga-robotics-raises-8-5m-to-fund-uk-growth-for-strawberries/
[95] Frank Knight (2023). *The Ukraine war impact on UK consumers*. Available at: https://www.knightfrank.com/research/article/2023-02-24-the-ukraine-war-impact-on-uk-consumers#:~:text=The%20impact%20of%20the%20Russian,farmers%20and%20rural%20businesses%20nationwide.
[96] Cranfield University (2022). *UK drought: are farmers facing the crop failures of 1976 all over again?* Available at: https://www.cranfield.ac.uk/press/news-2022/uk-drought-are-farmers-facing-the-crop-failures-of-1976-all-over-again#:~:text=July%202022%20was%20the%20driest,especially%20for%20fruit%20and%20vegetables.
[97] The Guardian (2022). *Up to £60m in UK crops left to rot owing to lack of workers, says NFU*. Available at: https://www.theguardian.com/environment/2022/aug/15/pounds-60m-in-uk-crops-left-to-rot-lack-of-workers-nfu-farming
[98] David Christian Rose, Mondira Bhattacharya, Adoption of autonomous robots in the soft fruit sector: Grower perspectives in the UK, *Smart Agricultural Technology*, Volume 3, 2023. Available at: Adoption of autonomous robots in the soft fruit sector: Grower perspectives in the UK - ScienceDirect

the quantity of pesticides. Although this may lead to a decline in the number of manual farming roles available, these negative effects are mitigated by the shortage of workers in the industry (few jobs to lose) and offset by growth in high-skilled roles in developing, manufacturing, integrating and maintaining robotic systems. By addressing the labour challenges faced by UK farms, robotic technologies have the potential to improve the resilience of the sector and reduce reliance on imports.

The **climate crisis and necessity of reaching net zero, whilst maintaining output,** is also acting as a powerful catalyst for innovation. For example, a key aim of Defra's Farming Innovation Programme is to reduce the environmental impact of agriculture and horticulture. Robots can optimise crop nitrogen use and reduce nitrogen dioxide emissions (through reducing fertiliser use), whilst AI-powered robots can reduce farm waste.[99] Small electrified robotic vehicles also have the potential to reduce emissions versus current large fossil fuel-powered farm vehicles (e.g. tractors etc.) and can operate cost effectively in smaller fields, allowing crucial field biodiversity to be maintained.[100] For example, Rickerby Estates have been supported by DEFRA as part of a consortium to develop a robotic harvester for short rotation willow coppice crops which can be grown on rewetted land to enable paludiculture. E-Nano and Lisst IO are using robotics to support biodiversity gain, and visioning specialist, Far Out Thinking Company, are developing vision systems including for robots to provide AI automatic biodiversity and ecosystem assessments. Though challenging market conditions in farming are generally stimulating and catalysing farming innovation, **agritech start-ups have also faced market and political instability**. The continuing threat of recession, alongside rising input prices and a tough investor climate puts pressure on key UK start-ups, especially those crossing the 'valley of death' from initial public funding to commercial viability. Robotics is a fundamentally hardware intensive technology area and so represents a high-risk opportunity to investors. There have been several previous company failures in the area of robotics which have further dampened the appetite for the sector amongst investors. Alongside this, UK firms face strong global competition. Notably, the Smart Robot Company lost their lead investor in January 2023 and faced redundancies to continue product development.[101]

Additionally, whilst challenging farming conditions provide a strong push factor to adopt robotics, they may also limit **farmers' ability to financially invest in this new technology**. Although other business models are being developed, e.g. by The Small Robot Company's subscription service, it is not just the cost of the robots themselves which must be considered, but also the necessary infrastructure, e.g. charging points. It is possible that cost-effectiveness in the long run may not be enough to guarantee adoption if farmers lack the capacity to invest

[99] Pearson et al. (2022). *Robotics and Autonomous Systems for Net Zero Agriculture*. Available at: https://link.springer.com/article/10.1007/s43154-022-00077-6

[100] Al-Amin, A.K.M.A., Lowenberg-DeBoer, J., Franklin, K. et al. Economics of field size and shape for autonomous crop machines. *Precision Agric* 24, 1738–1765 (2023). Available at: Economics of field size and shape for autonomous crop machines | SpringerLink

[101] Small Robot Company (2023). *Small Robot Co Consolidates to Focus on Optimisation*. Available at: https://www.smallrobotcompany.com/press-releases/2023/1/12/small-robot-co-consolidates-to-focus-on-optimisation

in this new technology.[102] However, in a dynamic sector we would expect that if one business cannot invest, a competitor will, squeezing out those without the capacity to invest.

Finally, the widespread adoption of robotic technologies in the UK must be underpinned by the correct infrastructure and skills. For example, some farms will not have sufficient internet connectivity or the necessary skillset to use robotic technologies. In addition to the skills of the end-user, aftermarket support will also need to be developed to meet distribution, servicing and maintenance needs.

Key assets and initiatives influencing UK capacity

Given the potential for robots to help farmers overcome significant external challenges in growing and harvesting and the wider net zero imperative (discussed in more detail below), there has been continued **strong government and wider public sector interest in developing this technology area** and ensuring UK firms are at the forefront of the move to automation.

The **UK's research strengths in underpinning technologies** (computer science, AI, engineering) are well-recognised. For example, AgriFoRwArdS, an EPSRC Centre for Doctoral Training, is a collaboration between the Universities of Lincoln, Cambridge and East Anglia, and is preparing to welcome its fifth cohort of PG students in October 2023, feeding the sector's skills pipeline. Lincoln Agri-Robotics (LAR), the world's first global centre of excellence in agricultural robotics, continues to lead robotic innovation in the sector, with involvement in 22 robots and automation research projects in agriculture.[103] LAR is launching a BSc in Robotics in September 2023 to complement the AgriFoRwArdS PhD programme and also has an MSc in AgriFood Technology with 100 students. It also started a supporting MSc in Data Analytics in 2022 which is focused on the underpinning data and computing expertise for robotics. The LAR have worked with crop breeders and imaging companies to develop high speed robotic phenotyping which can analyse field crop trials much faster than traditional approaches allowing more trial plots to be analysed with improved accuracy and at lower cost. This is now in trials with commercial companies and offers the potential to accelerate plant breeding. Plant breeders are also collaborating with robot development projects so that crop architecture can be 'redesigned' so that it makes them easier to harvest or treat using robots.

Significantly, in October 2021, in partnership with UKRI, Defra launched the first funding rounds for the Farming Innovation Programme. Of particular relevance for this review of agritech robotics, **a £12.5m robotics and automation competition** was launched in January 2023, offering up to £1.5m for collaborative projects focussed on robotics and automation in agriculture and horticultural production.[104] UK agri-robotics firms have also benefitted from

[102] David Christian Rose, Mondira Bhattacharya, Adoption of autonomous robots in the soft fruit sector: Grower perspectives in the UK, *Smart Agricultural Technology*, Volume 3, 2023. Available at: Adoption of autonomous robots in the soft fruit sector: Grower perspectives in the UK - ScienceDirect
[103] University of Lincoln (2023). *Our Research*. Available at: https://www.lincoln.ac.uk/liat/research/
[104] Department for Environment, Food & Rural Affairs (2022). *Funding available for robotics and automation in farming*. Available at: Funding available for robotics and automation in farming - Farming (blog.gov.uk)

other elements of the Farming Innovation Programme, for example, Muddy Machines received Small R&D Partnership Projects funding as part of the programme.[105]

Alternative Proteins

Alternative proteins are sources of protein that are derived from different natural ingredients such as plants, insects and algae, or artificially-developed ingredients such as cultivated meat.

Environmental, ethical and health concerns over animal proteins have grown in recent years in developed economies like the UK, driving increasing levels of interest and demand for the development of sustainable alternative protein products. Overall, demand-led innovations in food science, biotechnology and tissue engineering have been key to the development of alternative proteins products that could be widely adopted by consumers in the UK and elsewhere.

Proponents of alternative proteins claim that the sector puts less strain on resources than animal-based agriculture, and so adoption of alternative proteins can help deliver against the United Nations Sustainable Development Goals.[106] However, there is a growing body of research suggesting that the picture is not as clear-cut, for example lab grown beef has been estimated to be up to 25 times more polluting than traditional beef if produced using purified media.[107]

Technology maturity and application

The alternative proteins sector comprises several distinct sub-sectors which, despite sharing a common goal, are at various stages of maturity. The latest developments in four key sub-sectors are outlined below.

Plant proteins have formed part of human diets for millennia, though around half of the protein content in UK diets originates from four plant species: soya, wheat, corn and pea. Much of the R&D activity in alternative proteins has focused on diversifying the offer to develop new and improved plant-based products, some of which seek to resemble animal produce (e.g. meat and dairy). Most recognised plant-based protein sources have been approved in the UK for human consumption, and many UK-led natural ingredient-based innovations as alternative protein products (e.g. legumes, fungi and beans) have reached commercialisation. Some UK companies and products have been well-established for years, while more recent entrants have

[105] Department for Environment, Food & Rural Affairs, UK Research and Innovation and Steve Double (2022). *Boost for farming innovation*. Available at: https://www.gov.uk/government/news/boost-for-farming-innovation
[106] See, for example: UKRI (2022) Alternative Proteins: Identifying UK priorities; World Economic Forum (2021) Alternative proteins will transform food, mitigate climate change and drive profits. Here's how; World Economic Forum (2019) Meat: The Future. A Roadmap for Delivering 21st-Century Protein
[107] UC Davis (2023) Lab-Grown Meat's Carbon Footprint Potentially Worse Than Retail Beef

developed different products such as powders, bars and patties. While these products are currently in diffusion stage, i.e. present in some mainstream retail stores and supermarkets, they are typically not yet widely adopted by UK consumers (who nevertheless remain some of the leaders in adoption worldwide). There is also R&D activity looking at other sources of plant protein, including to extract potato protein from processing waste potatoes[108], using brassica waste to produce protein products[109], and the recently announced £1m research project into using pea protein as a sustainable alternative to soya.[110]

The Good Food Institute expects moderate growth for the global market in the short-term as consumers grapple with the lingering effects of inflation despite growing levels of interest in plant-based alternatives.[111] Rabobank, a specialist investor, is even less optimistic, referring to a market shift in 2022 and predicting "a year of consolidation" in 2023.[112] Indeed, there have been some recent worrying signs, with Beyond Meat – one of the key players globally – cutting its revenue forecasts by a third[113], and UK-based Plant & Bean and Meatless Farm close to collapse[114] prior to being acquired.[115] To some extent, this reflects the wider challenges faced by the sector, including high interest rates and energy costs. However, it has also been argued that this represents a market adjustment in response to a saturated market, as well as unrealistically optimistic valuations and growth expectations over the last decade.[116]

Cultivated meat[117] is grown in vitro, directly from animal cells. While this field is still nascent, it has been gaining momentum with considerable advances over the last few years. Despite the challenging market environment, 2022 saw the largest private investment deals to date globally with a growing number of unique investors interested in cultivated meat.[118] Whilst this seems to suggest that cultivated meat has benefitted from investor focus shifting away from plant-based proteins, it is noted that this field has been affected by the significant challenges facing the alternative proteins sector as a whole (including high interest rates and energy prices) as well as those specific to this sub-sector (e.g. consumer acceptance).

The Good Food Institute mapped 17 UK cultivated meat and seafood companies in 2022 – the second highest figure behind the US (43) and level with Israel.[119] The same year, Ivy Farm

108 https://www.rootextracts.com/
109 https://naylornutrition.com/
110 Aberystwyth University (2023) £1 million pea protein research aims to cut soya imports
111 GFI (2022) State of the Industry Report: Plant-based meat, seafood, eggs, and dairy
112 Rabobank (2022) Global Animal Protein Outlook 2023
113 AFN (2023) Beyond Meat CEO under fire after grim Q2, 2023 results: 'The overall pie is not growing'
114 Just Food (2023) Plant & Bean calls in administrators; Vegconomist (2023) Meatless Farm back on shelves less than a month after facing administration
115 BBC (2023) Boston vegan food producer bought by Heather Mills' group
116 Rabobank (2022) Global Animal Protein Outlook 2023; Rabobank (2023) A Path for Plant-based Meat out of the Trough of Disillusionment: Consolidation Seems Inevitable in Europe
117 Cultivated meat is synonymous with various other terms, including 'lab-grown', 'cell-cultured' and 'in vitro' meat. In October 2022, the APAC Society for Cellular Agriculture announced a new Memorandum of Understanding stating that 'cultivated' is the preferred English-language term for the field. See also: GFI (2022) Leading APAC Cellular Agriculture Stakeholders Announce Historic Agreement in Singapore
118 GFI (2022) State of the Industry Report: Cultivated meat and seafood
119 Ibid.

Technologies opened a new pilot production plant in Oxford capable of producing 2.8 tonnes of cultivated meat per year – the largest of its kind in Europe.[120] However, the UK (and Europe more widely) is lagging behind in commercialisation, with the first comparable products in Singapore reaching the market in 2020 (though the extent to which these are widely available has been questioned[121]), and the US gearing up to follow in its footsteps after the first-ever full approval to sell cultivated meat products in June 2023.[122] The UK's first application to sell cultivated meat was submitted by Israel-based Aleph Farms in summer 2023[123] but had not yet been approved at the time of this report. It remains to be seen whether cultivated meat is able to overcome the challenges it is facing to reach commercial maturity and scale.[124]

Fermentation[125] is another route to producing alternatives to conventional proteins. This includes precision fermentation that uses microbes as "cell factories" for producing specific functional ingredients, and can be used to enhance the sensory properties of plant-based protein products or cultivated meat (e.g. by adding new or reducing unwanted flavours/aromas). There has been growing interest in this field globally, with the number of unique investors in fermentation increasing by 38% in 2022, though the amount of investment decreased year-on-year, mirroring similar trends in other markets due to challenging macroeconomic conditions.[126] The Good Food Institute[127] identified seven fermentation-enabled companies in the UK in 2022 – the fourth highest figure behind the US (42), Israel (11) and Germany (10). Key companies in the UK include Quorn which for over a decade was the only brand of meat alternatives made from something other than plant proteins (mycoprotein).[128]

Other novel proteins include sources such as insects (e.g. crickets and black soldier flies) and novel aquaculture (e.g. spirulina and seaweed). For example, SeaGrown in Yorkshire has developed a novel method for seaweed farming. Some of these products are already available to UK consumers, with Sainsbury's leading the way in 2018 as the first supermarket to stock edible insects.[129] However, the full extent of opportunities in this area remains largely untapped – the insect protein industry is dominated by a few species, and less than 20 seaweed species are being used (and this is mostly for non-protein uses or to be used in livestock and

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[120] Vegconomist (2022) Ivy Farm unveils Europe's biggest cultivated meat pilot production facility
[121] BBC (2023) Why Singapore is the only place in the world selling lab-grown meat
[122] Reuters (2023) 'A new era': US regulator allows first sales of lab-grown meat
[123] FoodNavigator (2023) UK's first cultivated meat approval submitted
[124] AFN (2023) Cultivated meat: Foodtech fantasy or the future of meat? 'None of this stuff makes any commercial sense until everyone's eating it'
[125] From GFI (2022) State of the Industry Report: Fermentation: Fermentation refers to cultivating microbial organisms for the purpose of processing a foodstuff or food ingredient; obtaining more of the organism itself as a primary source of protein; or deriving specialized ingredients (e.g. flavourings, enzymes, proteins and fats) for incorporation into plant-based products or cultivated meat. Fermentation is generally divided into products of traditional fermentation, biomass, and functional ingredients (produced via precision fermentation).
[126] Ibid.
[127] Ibid.
[128] Food Dive (2022) Fermentation leaders form Fungi Protein Association
[129] The Guardian (2018) Bug grub: Sainsbury's to stock edible insects on shelves in a UK first

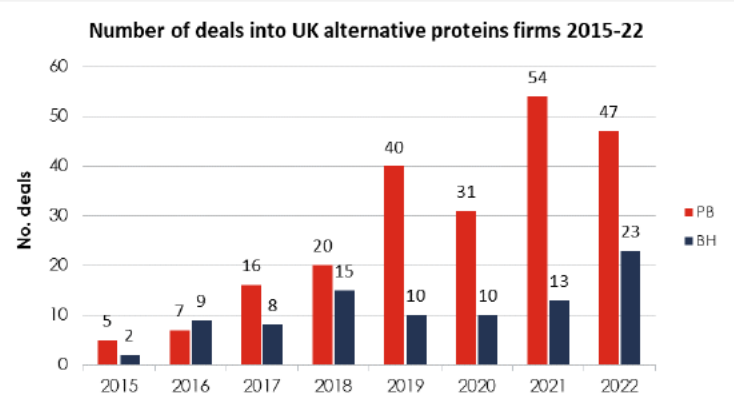
fish feed).[130] These sectors comprise a small number of startups or small companies, characterised by low production volumes and limited opportunities to compete with cheaper sources of protein such as soya bean. In addition to a complex regulatory landscape (with only some insect species being cleared for use in food and feed), consumer awareness and acceptance remains a challenge.

Key recent developments and trends in the technology area

Investment

The UK's alternative proteins sector has seen substantial investment over recent years. Although figures vary by source (given challenges in accessing data on private investment), for the latest full year (2022) Pitchbook (PB) estimates £174m of investment[131] in UK alternative proteins firms[132] (via 47 deals) and Beauhurst (BH) provides a corresponding figure of £80m (via 23 deals). For context, the UK investment data from PB for 2022 accounts for 23% of the total investment across Europe (£756m) and 7% globally (£2.5bn) in this sector. Over the last five years (2018 to 2022), PB indicates an average of 38 deals per year closed by UK alternative proteins firms (in aggregate, c. £433m via 192 deals) whereas BH suggests an average of 14 deals per year (c. 192m via 71 deals).

There is considerable fluctuation in the value of investment year-on-year, reflecting the specialist nature of the area as well as the impact of a small number of large investments on the totals. However, looking at the period 2015-2022, data on the number of deals does suggest an overall positive trajectory (see the graph below), indicating growing interest in this area from the investment community. The quantitative data analysed for this report do not lend itself to commenting on the apparent market shift in some alternative proteins segments (as indicated by qualitative evidence above), for two reasons: first, the data cover the whole alternative proteins sector rather than specific sub-sectors; and second, it would be too early to comment on the full impact of any shifts in the last couple of years (given annual fluctuations). Anecdotal evidence from the workshop suggests that over the last few years, investors have been favouring follow-on investments into existing portfolio companies, thus limiting the amount of capital available for new entrants.



[130] UKRI (2022) Alternative Proteins: Identifying UK priorities
[131] Note that this includes four deals of £20-25m each.
[132] UK companies on Pitchbook are defined as those with the HQ in the UK. On Beauhurst, this includes companies with HQ (where known, or registered address if not) in the UK.

Looking at the sources of investment into UK alternative proteins companies, there is a mix of UK and overseas investors. Among the top ten funds by value of investment, there are four fund managers headquartered in the UK and four in Europe (with no data on the other two). The picture is somewhat different when looking at funds by *number* of investments, with most of the top investors headquartered in the UK (including Kelvin Capital, Scottish Venture Fund, the University of Cambridge Seed Funds and University of Cambridge Enterprise Fund), suggesting smaller but more deals closed by local funds.

Importantly, there is also significant investment in the sector from mainstream established food processors investing in additional plant protein capacity. For example, Princes (owned by Mitsubishi Corporation) has made significant investment to expand its production in Long Sutton in Lincolnshire, mostly focused on expanded pea production.

Wider technology and market trends

The Beauhurst database tracks 34 high growth alternative protein companies headquartered around the UK, notably in London, Yorkshire, East Midlands, the South East and Scotland. Key investors in these companies include the University of Strathclyde, Scottish Enterprise and Data Collective, responding to companies' need to accelerate R&D and increase their resources to reach commercialisation.

In considering key changes since the baseline report in recent years drawing on the findings above, the picture is mixed. With regards to the more mature sub-sectors, there have been some worrying signs in the market, especially for plant-based proteins. Although there has been growing interest and activity in cultivated meat, the sector faces significant challenges on the way to commercialisation. The UK has not caught up with early movers in this space (particularly Singapore and the US). Fermentation and other types of novel proteins remain at an early stage of development.

Factors influencing the technology areas in the UK

There is some concern that the UK is lagging behind competitor countries that have more developed alternative protein markets, including the Netherlands and Israel. Despite increasing funding commitments, **the UK does not have an overarching national strategy** for alternative proteins, and it is unclear who is (or should be) leading on this agenda. There have also been calls for government to earmark funding in its £120m pledge for sustainable proteins.[133]

The **regulatory environment** in the UK and the EU, which are important markets, may pose barriers to the commercialisation, diffusion and adoption of alternative protein technologies. This includes labelling restrictions and a 'legal blur', which may notably restrict the use of

[133] GFI (2022) GFI Europe calls for coordinated funding after UK Government pledges to support sustainable proteins

words such as “meat”, “milk”, “burger” and “sausage”.[134] Additionally, cultivated meat as well as many insect proteins are not yet fully approved as food in the UK or the EU, and the current regulatory approval process is struggling to keep up with the pace of innovation.[135] Whilst the current processes have been criticised for their slow turnaround and a lack of transparency, legislation in this area continues to develop, with latest developments including a review of the novel foods regulatory framework published by the UK Food Standards Agency.[136] Italy, however, is moving towards banning cultivated meat production and imports.[137]

Alternative protein products tend to be sold at a **significant price premium** compared to conventional products, and price parity with meat and other animal products has not yet been reached. A continuing cost push is the price of energy, with these production techniques often very energy intensive. This price premium may hinder widespread adoption by UK customers – particularly against the backdrop of the ‘cost of living crisis’ which has tightened household budgets. Much like the broader food sector, the alternative proteins supply chain has suffered from disruptions (including due to the rising energy costs) and ingredient shortages caused by Covid-19, the war in Ukraine and avian flu outbreaks. However, the price gap between substitutes and animal protein products has been reducing over the last couple of years, with conventional meat products seeing considerable price increases.[138]

The **cost of technologies** used to produce cultivated meat and other lab-grown food is considerable, as these were often not developed with mass production in mind (often being medical/pharmaceutical technologies), representing an obstacle to product scale-up. Production of plant-based proteins requires a high enough yield to meet the necessary scale implemented by the food industry (and achieve cost and emissions reductions through scale). This means that companies are required to make large upfront investments in infrastructure prior to generating sales. It is therefore essential for companies to secure early-stage capital funding externally, but there are barriers to accessing conventional sources of finance (e.g. through banks and venture capital) due to the lack of track record and level of risk involved.

In addition to developing the product and enabling affordable scale up, **consumer acceptance** regarding the process and sensory experience of alternative proteins products remains a challenge. For many people, there are deep cultural and psychological ties to conventional animal produce. Recent evidence suggests that representing foods as vegan reduces their appeal to consumers, as many actively reject vegan/plant-based labelled food.[139] Concerns have also been raised over potential adverse health impacts of ‘ultra-processed’ meat substitutes. It may take a decade or more for many of the newer alternative protein

[134] Reuters (2023) France makes fresh bid to ban meat names for plant-based food
[135] AFN (2022) UK alternative protein: UK could be leader with faster regulation, more funding for cell ag
[136] FSA (2023) Novel Foods Regulatory Framework Review: Executive Summary
[137] Forbes (2023) Italy gets one step closer to ban cultivated meat production and imports
[138] Rabobank (2022) Global Animal Protein Outlook 2023
[139] FoodNavigator (2023) Want more people to buy your vegan or vegetarian products? Then don’t label them as such

technologies to reach full commercialisation, meaning investors may need to accept time horizons that stretch beyond the conventional shorter-term VC fund cycle.

Key assets and initiatives influencing UK capacity

The UK has a **very active R&D community focused on developing alternative protein technologies**. According to the 2023 Nature Index, the UK is a world leading contributor in natural and health sciences (ranked 4th globally and 2nd in Europe).[140] Research in this subject area can be, and has been, leveraged to escalate alternative protein R&D by providing expertise in stem cell, cell culture, and regenerative medicine, which are especially important for cultured meat/lab-grown foods research.

The UK also builds on the **expertise and academia-industry collaborations** developed through research and innovation centres focusing on areas relevant to alternative protein technologies. Examples include:

- the Food Innovation Centre at the University of Nottingham, which has led several research projects into the utilisation and acceptance by consumers of alternative proteins as a food source
- the Centre for Sustainable Energy Use in Food Chains; the National Centre of Excellence in Food Engineering at Sheffield Hallam University
- the John Innes Centre in Norwich which has breeding programmes for plant protein crops such as peas and a World leading seed bank for these crops
- the recently announced Cellular Agriculture Manufacturing Hub led by the University of Bath and involving a wide range of research and commercial partners (including Hoxton Farms, 3D Bio-Tissues, Ivy Farm and Quest Meat), which aims to position the UK as a leader in cultivated meat research.

Research and technology are also continuously developing in related fields where the UK has major strengths and assets (e.g. medicine, chemistry), enabling further alternative protein innovations.

Increased activity in food research and growing demand/pressure for alternative proteins have also resulted in **UK institutional, government and industrial investment to boost R&D** in this field. The UK government's commitment to net zero by 2050 has helped to advance this agenda, owing to the role of alternative proteins in reducing the environmental impact of the food system. The Government Food Strategy in 2022 pledged £120m of investment through UKRI in research across the food system.[141] In 2022, UKRI published its roadmap for alternative proteins, setting out the challenges and opportunities for three priority sectors: plant-based;

[140] https://www.nature.com/nature-index/annual-tables/2023/country/all/all
[141] DEFRA (2022) Government Food Strategy

fermentation; and novel systems.[142] In 2023, the Biotechnology and Biological Sciences Research Council (BBSRC) announced £15m of funding for an Alternative Proteins Innovation and Knowledge Centre.[143]

142 UKRI (2022) Alternative Proteins: Identifying UK priorities

143 https://www.ukri.org/opportunity/alternative-proteins-innovation-and-knowledge-centre/

Annex F: Further evidence from surveys

Beneficiary survey (Phase 5)

Pre-intervention experience and capabilities

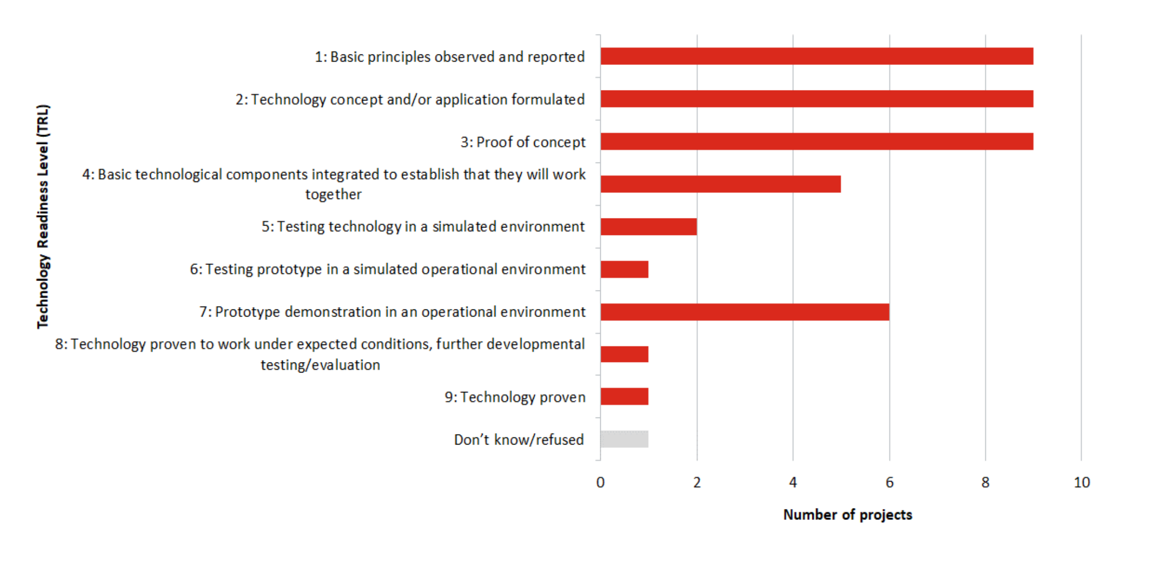
F.1 *Note, this data combines responses from the baseline and new respondents in the Wave 2 survey (i.e. those who did not complete the baseline).*

F.2 In terms of the participants responding to the survey:

- Most beneficiaries had prior collaborative R&D experience. For example, of the beneficiaries for whom we have pre-intervention data, 89% (120/135) had invested in R&D for the purposes of innovation in the three years prior to applying for TFP funding, and around three quarters (76%, 103/135) had done so in collaboration with others.
- TFP has attracted those with limited or no experience of R&D in agri-food sector. Over half of respondents (n=135) had extensive experience of R&D in agri-food (56%), but the remainder had limited (27%) or no (14%) experience of this sector. And TFP has engaged with organisations who had not received other public sector support for R&D in the three years prior to TFP (39%).
- There is also evidence of TFP projects involving end users and facilitating new partnerships to form, including working with private sector partners for the first time.

F.3 In terms of the projects, at the time of TFP applications, data from leads suggests the majority of projects were at TRLs 1-4 (across all strands). Most later stage projects (TRL 7-9) were STiP.

Figure F-1: TRL position at the time of TFP application (leads only, n=45)



Source: SQW analysis of beneficiary survey

Unsuccessful applicant survey (Phase 5)

Pre-application experience/capabilities

F.4 The majority of UA respondents[144] had prior collaborative R&D experience, slightly less so compared to the beneficiary sample. For example[145]:

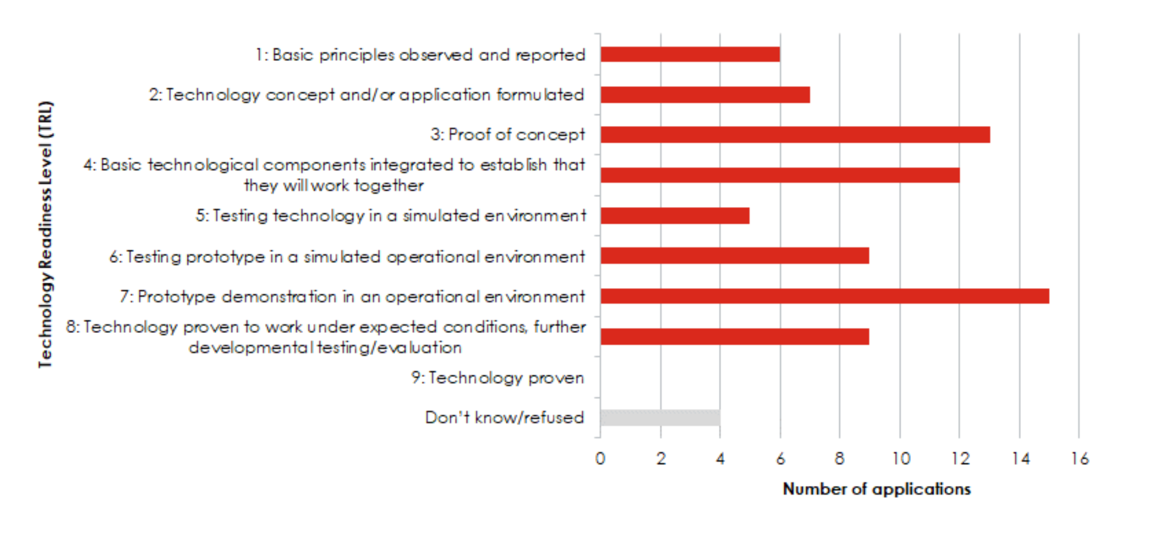
- 76% of UA respondents had invested in R&D for the purposes of innovation in the three years prior to applying for TFP funding (cf. 89% for beneficiaries)
- 65% had done so in collaboration with others (cf. 76% for beneficiaries)

F.5 UAs were slightly less likely to have prior experience of R&D in agri-food sector (70%) compared to beneficiaries (83%).[146] Moreover, of those UAs who did have prior experience of the sector, they were less likely to have 'extensive' experience (55%) compared to beneficiaries (67%), although this is not significant.

F.6 At the time of TFP applications, data from UA leads[147] suggests the proposed projects were spread across the TRLs (more so than the beneficiary projects), with less emphasis on earlier stage technologies.

[144] N=188. Note, this data combines responses from the baseline and new respondents in the Wave 2 survey (i.e. those who did not complete the baseline)
[145] statistically significant differences at the 5% confidence level
[146] statistically significant differences at the 5% confidence level
[147] N=80. Note, this data combines responses from the baseline and new respondents in the Wave 2 survey (i.e. those who did not complete the baseline)

Figure F-2: TRL position at the time of TFP application (leads only, n=80)



Source: SQW analysis of UA survey

Wider sector survey (Phase 5)

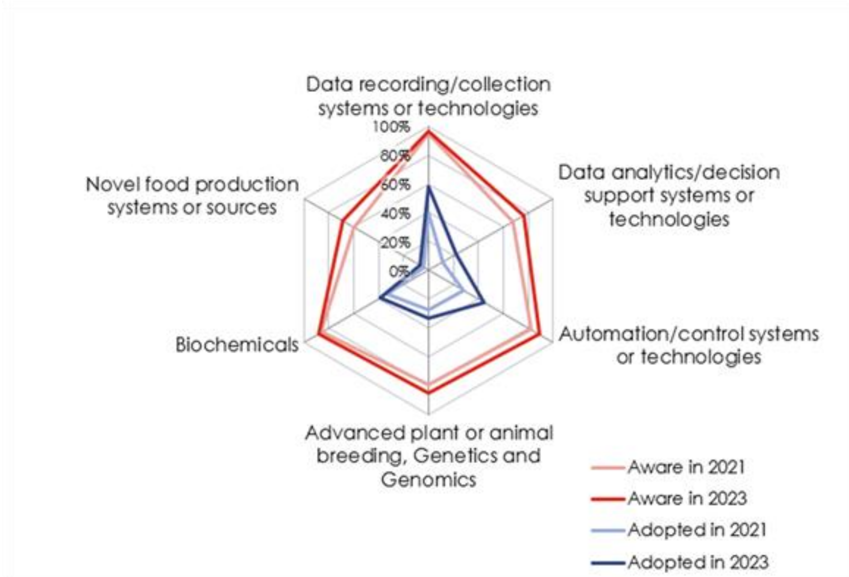
F.7 The wider sector survey (Wave 2) was a survey focussed on the awareness and adoption of innovative technologies by those in the wider agricultural sector (i.e. not those directly involved with a Transforming Food Production grant). This built on a Wave 1 survey conducted earlier. Key findings are laid out below:

F.8 **Awareness has increased** since the Wave 1 survey across all of the six key technologies amongst the 126 respondents completing both surveys. The greatest shifts in awareness are in the areas of data analytics and novel food production systems or sources. In addition, adoption of technologies has increased, **greatest is in 'data recording/collection technologies' and 'automation/control systems'** (an increase of 18pp and 16pp respectively), followed by 'data analytics/decision support systems' (11pp) whilst there has been little or no increased adoption of 'advanced plant/animal breeding and genetics', 'biochemicals' and 'novel food production systems or sources'. This is demonstrated in Figure F-3.

F.9 **There remains a large 'gap' between the level of awareness and adoption across all technologies**. The gap was largest for novel foods (as expected) followed by data analytics/decision support systems: e.g., even though three-quarters of respondents were aware of data analytics/decision support systems, only around a quarter of those aware had actually adopted those technologies. The gap between awareness and adoption has narrowed most for data recording/collection technologies since Wave 1. The gap has also narrowed for automation/control system, but there is little change in the gap for data analytics/decision support technologies or genetics etc.

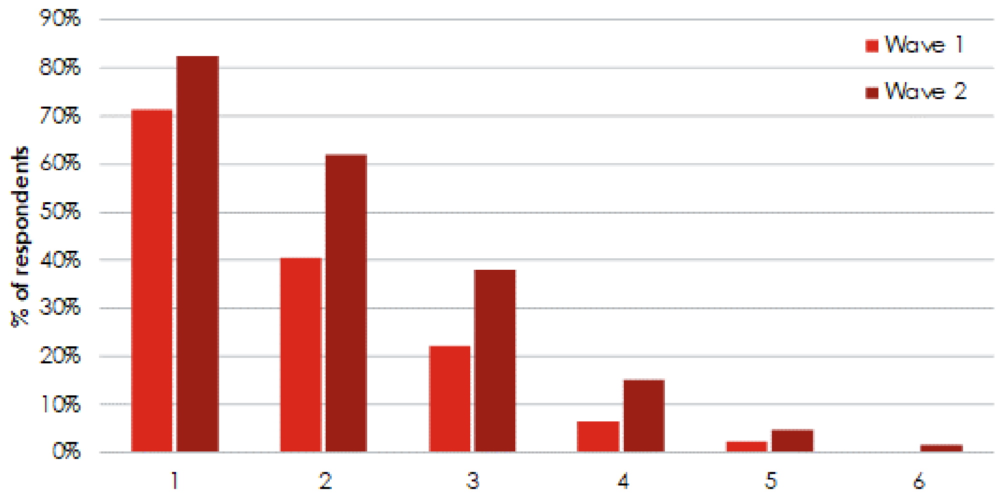
1.8 Since the Wave 1 survey **the proportion of respondents adopting single and multiple technologies has increased.** 83% of the survey sample (104 of the 126) has adopted at least one of the six technologies in Wave 2, a substantial rise on the 71% that had adopted at least one technology at the Wave 1 survey stage. Similarly, the proportion of respondents reporting adopting 2, 3, 4, 5 or 6 of the technologies also increased (Figure F-4:).

Figure F-3: Adoption and awareness of agritech technologies in the wider sector (n = 126)



Source: SQW Analysis of TFP Wider Sector Survey Data

Figure F-4: Adoption of number of technologies (n = 126)



Source: SQW Analysis of TFP Wider Sector Survey Data

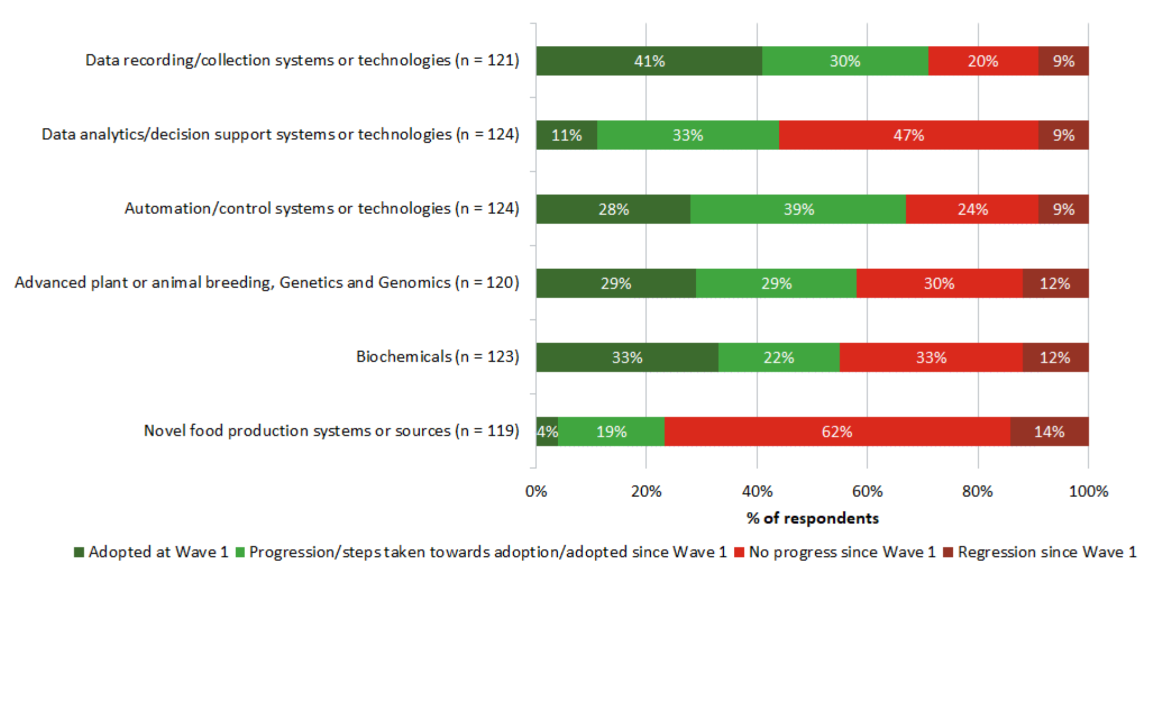
F.10 Where businesses had not adopted technologies, there was still evidence that they had progressed towards adoption (i.e. taking steps towards adoption). In absolute terms, **most**

progress has been made in automation/control systems, where nearly two fifths of respondents have taken steps towards adoption since Wave 1 (in addition to 28% who had adopted by Wave 1). By Wave 2, 67% of respondents had adopted or were taking steps towards the adoption of automation/control systems.

F.11 Progress towards adoption is also encouraging for **data recording/collection systems,** whereby 71% of respondents had adopted or were taking steps towards adoption by Wave 2.

F.12 Whilst notable progress has been made towards adopting data analytics/decision support systems, this started from a low base in Wave 1 and over half of respondents have made no progress or moved away from adoption since Wave 1. **Encouraging the adoption of data analytics/decision support systems appears to be challenging**.

Figure F-5: Adoption, Progression and Regression of technologies since the wave 1 survey (n = varies)



Source: SQW Analysis of TFP Wider Sector Survey data

F.13 Those that had adopted were asked to identify which benefits their business had experienced as a result of adoption. The observed benefits are broadly consistent across technologies, particularly in relation to the most commonly identified outcomes such as increased efficiency/accuracy or inputs, improved understanding/insight to inform business strategies, and better informed decision making. Across all technologies, approaching half (47%) reported that the adoption of the technology had led to a reduction in carbon emissions. Similarly, 48% of respondents report that adoption had affected turnover or profitability (53%). Most commonly the increase in these was <10%.

F.14 The data highlight the range of benefits from technology adoption. For example, many of the technologies have reduced environmental degradation and carbon emissions, as well as increasing yields, reducing costs and increased efficiencies – i.e. achieving positive externalities as well as financial benefits for the business.

F.15 The technologies appear to have less impact on markets (expanding into existing markets or diversifying into new markets). There is also limited evidence of impacts on the need for labour, perhaps more surprisingly given adoption rates for automation/control systems above.

Figure F-6: Benefits of adopting technologies (n = varies)

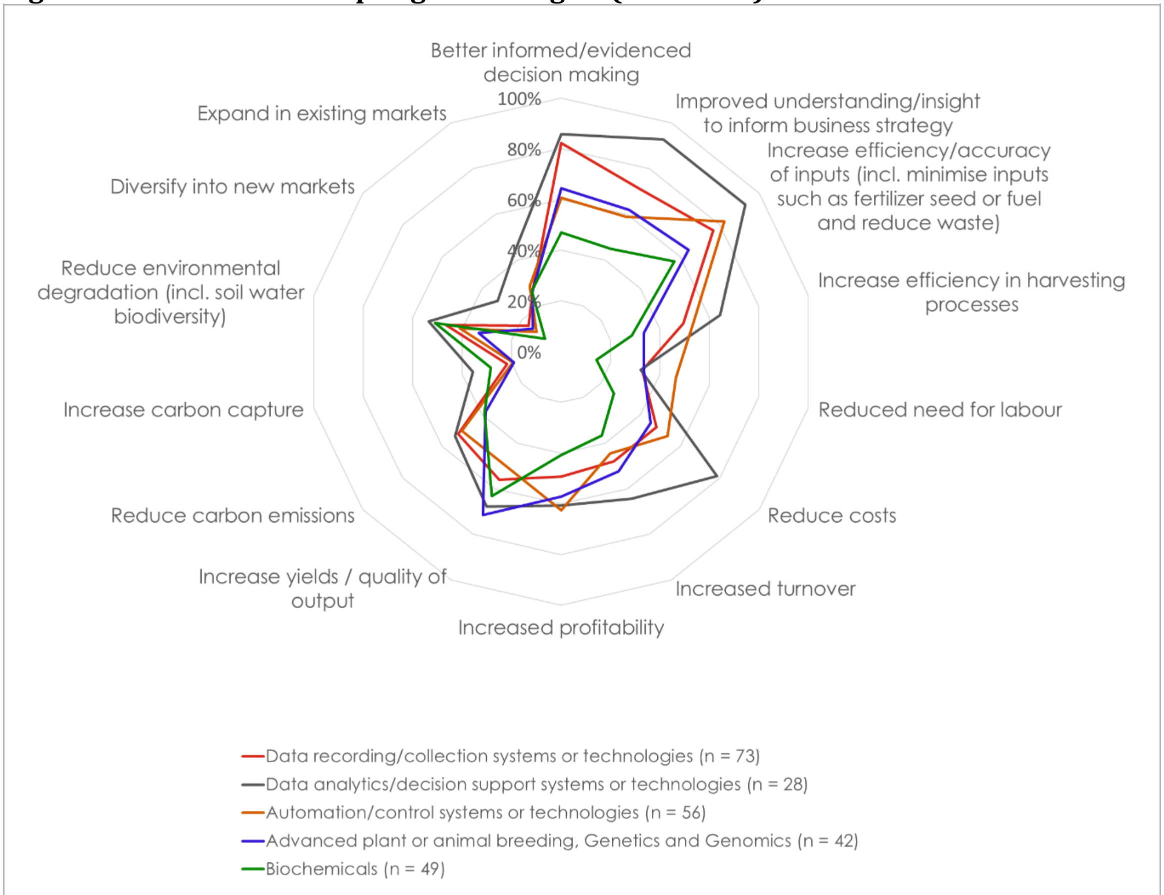
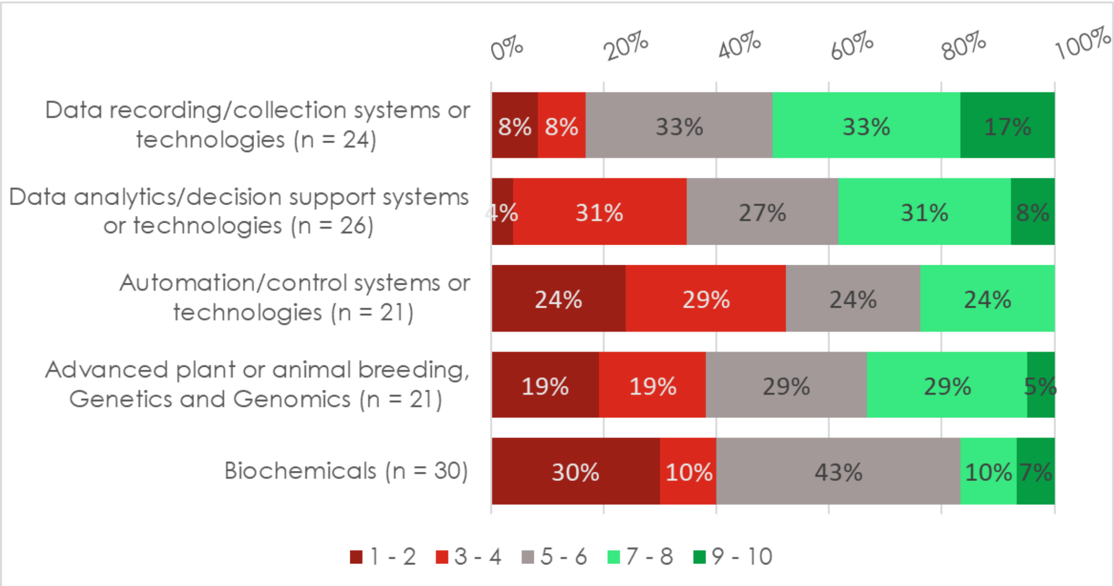


Figure F-7: Source: SQW Analysis of wider sector data
Note: Those who had adopted 'novel food production systems or sources' were excluded due to their small number (n = 9)

F.16 **Those who had not adopted each technology** but intended to adopt in the future or those who would look further into it were asked how likely they were to adopt this technology in the next five years on a scale of one (no chance) to ten (absolutely certain). The full results are laid out in Figure F-7: : **Data recording/collection systems technology is most likely to be adopted in the next five years**. However, there is a large gap between intentions to adopt and actual adoption – only approximately one-third of business that were absolutely certain they would adopt a technology at the wave 1 survey had by the wave 2 survey.

F.17 **The most common reason for not adopting was that the technologies were not appropriate for the business,** followed by expense and uncertainty and risks about benefits.

Figure F-7: : Likelihood of adoption of technology in the next two years (n = varies)



Source: SQW Analysis of TFP Wider Sector Survey Data

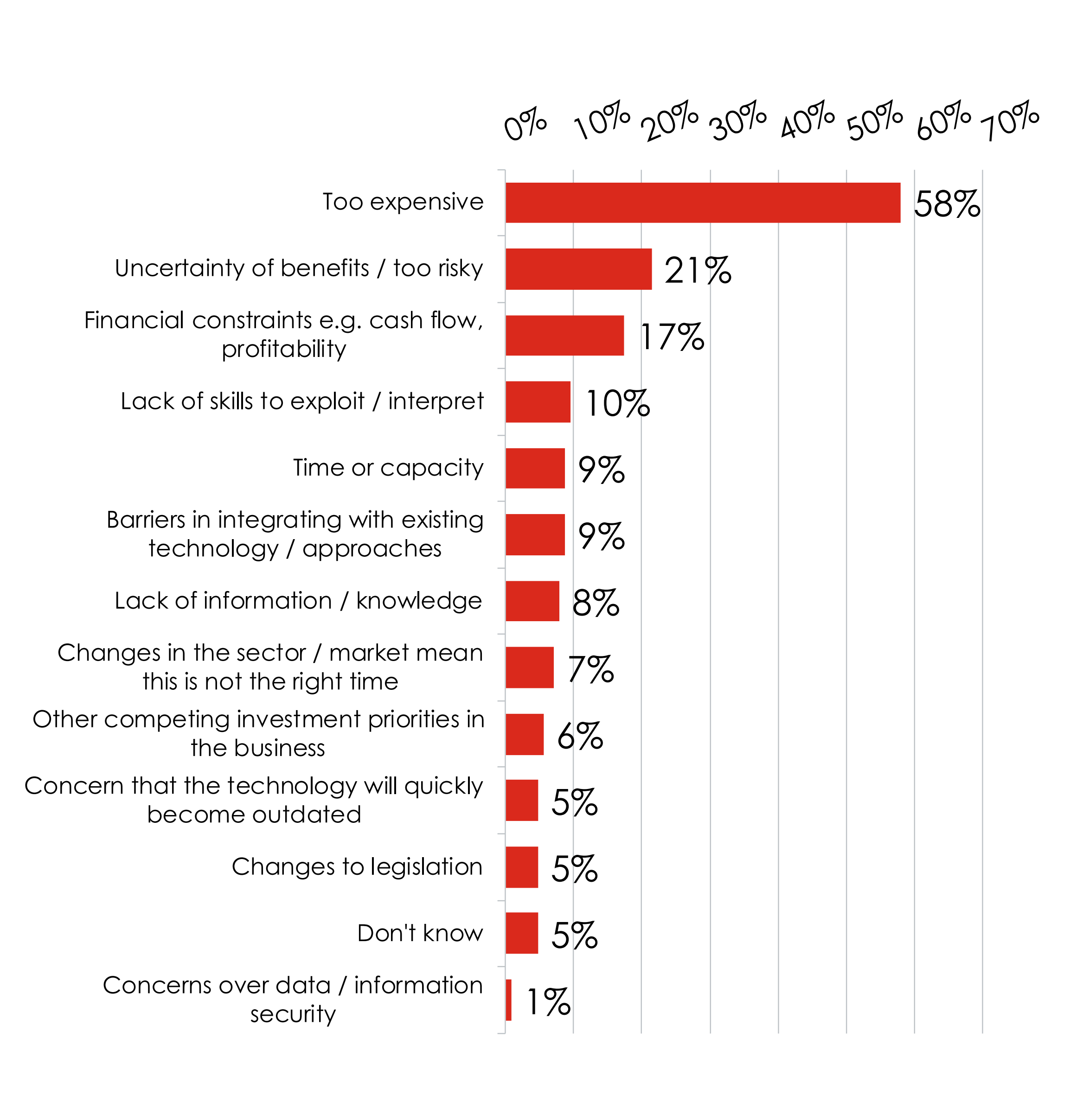
Note: Those who planned to adopt 'novel food production systems or sources' were excluded due to their small number (n = 13)

F.18 All respondents (regardless of adoption status) were also asked what factor and barriers to the adoption of future technologies there are.

F.19 Factors influencing adoption included cost pressures (31%, 39/126), financial viability (22%, 22/126) and responding to policy/regulatory changes (15% , 19/126).

F.20 The main barrier to adoption was costs or cost-related, with costs cited by 58% of respondents (73/126), the uncertainty around benefits from adoption being too risky (21%, 27/126) and financial constraints (17%, 22/126). A full breakdown is shown in Figure F-8:

Figure F-8: Barriers to future adoption of technologies (n = 126)



Source: SQW Analysis of TFP Wider Sector survey data

Annex G: Detailed econometrics and quantitative futures methodologies and analysis

G.1 This Annex provides further detail about the econometric analysis of impacts of TFP support on beneficiaries and Monte Carlo modelling of expected additional turnover generated by them.

Econometric analysis results

G.2 The tables below show full results for Tables 7-1 and 7-2 in the main report.

Table G-1: DiD analysis of employment and turnover impacts of TFP

Outcome:	Log (employment)		Log (real turnover)	
Comparison group:	1) BSD, matched with PSM	2) UAs	1) BSD, matched with PSM	2) UAs
Impact of TFP	0.132**	0.020	-0.031	-0.018
	(0.061)	(0.052)	(0.105)	(0.100)
Group trend of participants	0.051***	0.010	0.067***	0.055**
	(0.012)	(0.010)	(0.026)	(0.024)

*Standard errors in parentheses, level of statistical significance: * p < 0.1, ** p < 0.05, *** p < 0.01. All regressions controlled for year fixed effects and business fixed effects*

Source: SQW analysis of ONS data

Table G-2: DiD analysis of other impacts of TFP (latest position compared to pre-TFP)

Outcome	DiD estimate: treatment effect
Have participants increased R&D spending more than UAs?	0.155 (0.484)
Are participants more likely to become businesses that invest in R&D following TFP than UAs?	0.008 (0.078)
Have participants increased the Technology Readiness Level (TRL) by more than UAs?	2.074** (0.833)
Have participants increased their productivity (turnover/employment) by more than UAs?	27,868 (317,670)
Have participants increased their R&D spend per person by more than UAs?	747.76 (26,861)
Are participants more likely to export part of their turnover following TFP than UAs?	0.207* (0.106)
Have participants increased their company valuation by more than UAs?	0.275 (0.511)

Outcome	DiD estimate: treatment effect
Have more participants started to collaborate on R&D following TFP than UAs?	-0.057 (0.090)
Have more participants had other R&D support following TFP than UAs?	0.026 (0.101)

*Annex C: Standard errors in parentheses, level of statistical significance: * p < 0.1, ** p < 0.05, *** p < 0.01. All regressions account for pre-existing differences between treatment and control groups*

Source: SQW analysis

Monte Carlo modelling

G.1 The Monte Carlo modelling involved the following seven steps:

- **Step 1: Specifying the starting position for the population of TFP-supported projects**, including start year, starting TRL and the number of business collaborators
- **Step 2: Simulating the TRL progression of TFP-funded projects over the years**, taking into account the average speed and variance in progress of TFP-supported projects
- **Step 3: Calculating the present value of turnover generated by successfully commercialised projects.** This step took into account that not every TRL 9 project would become a commercial success as well as that the scale of turnover benefits varies across projects and between leads and collaborators. All turnover expected to be generated beyond 2023 was discounted.
- **Step 4: Calculating the total turnover expected to be generated by the programme** (by summing across projects)
- **Step 5: Repeating the same process (Steps 2 - 4) under the counterfactual scenario** i.e. by applying slower TRL progression (as observed among unsuccessful applicants), and recognising that only a proportion of the projects would have been taken forward without TFP backing.
- **Step 6: Calculating net additional turnover attributable to the programme.** This step involved finding the difference between the estimates obtained under the actual and counterfactual scenarios, i.e. the difference between turnover we expect the beneficiaries to generate with TFP funding and what they would have generated had there been no TFP support. The difference was further corrected to account for displacement – some innovations developed by beneficiaries may displace products and services currently offered by UK-based firms.
- **Step 7: repeating the calculations 10,000 times.** Each time a slightly different set of parameter values (e.g. turnover uplifts) were drawn from pre-determined statistical distributions yielding different estimates for the net additional turnover. At the end of

the process, we obtained the mean value of the estimate as well as the range of possible values, the 95% confidence interval and the relative likelihoods of different estimates.

Assumptions behind the Monte Carlo model

G.2 Table G-3: outlines all the assumptions and specific parameter values used in the model, and specifies the evidence underpinning those assumptions. Overall, **the model relied on baseline and final surveys of beneficiaries and unsuccessful applicants, and on results of econometric analysis.**

Table G-3: Parameters used for Monte Carlo simulations

Parameter	Value	Source/evidence/comments
Profile of the programme		
Number of projects	• 95	SQW Baseline overview report (2021). and monitoring data[148]
Profile of start years	• 2017: 30%; 2018: 30% • 2019: 30%; 2020: 10%	Monitoring data
Profile of TRL levels at the start of the programme	• TRL 1: 15%; TRL 2: 20% • TRL 3: 30%; TRL 4: 15% • TRL 5: 6%; TRL 6: 6% • TRL 7: 4%; TRL 8: 2% • TRL 9: 2%	Baseline surveys of beneficiaries and unsuccessful applicants
Proportion of leads among supported businesses (vs collaborators)	• 45% •	Monitoring data
Proportions of projects by number of collaborators	• One: 45%; Two: 40% • Three: 5%; Four: 5% • Five to eight: 5%	Monitoring data. We assumed a uniform distribution (i.e. approximately equal number) of projects that had between five and eight business collaborators
Outcomes		
Commercial success rate for projects reaching TRL 9	• 60%	Survey of beneficiaries adjusted for possible optimism bias and sample

[148] For modelling purposes, some parameters were rounded e.g. 94 projects to 95. Since the estimation procedure involves sampling around central parameters this rounding does not affect the overall findings. One way to think about the model is to imagine is trying to replicate the programme 10,000 times. Each 'version' of the programme would look slightly differently

Parameter	Value	Source/evidence/comments
		selection. The raw rate reported in the survey was c. 80%[149]
Proportion of collaborators that also experience an uplift in turnover in the case of commercial success	35%	Survey of beneficiaries
Speed of annual TRL progression	Normal distribution Mean with TFP: 1.2 St. dev. with TFP: 0.2 Mean without TFP: 0.4 St. dev. without TFP: 0.25	Econometric analysis of data from the baseline and impact surveys of beneficiaries and unsuccessful applicants
Proportion of projects that would have been taken forward even without TFP funding	35%	Survey of unsuccessful applicants
Average annual uplift in turnover for commercialised projects	Log-normal distribution Mean for leads: £1.2m St. dev. for leads: £2.3m Mean for collaborators: £0.9m St. dev. for collaborators: £2.8m	Survey of beneficiaries, based on the question about expected turnover over the next three years. The log normal distribution is non-symmetrical and skewed towards lower values. In other words, a larger proportion of beneficiaries is assumed to experience an uplift in the £0 - £1m range with a long tail of more successful 'outliers'. Parameters of the modelling distributions were selected to match the average, standard deviation and overall shape of the distributions observed in the sample.[150]
'Ramp up' in turnover uplift following reaching TRL 9	Year 1: 20% Year 2: 50% Year 3: 80%	Survey of beneficiaries. The turnover generated by a successful project was assumed to increase gradually. The values for this parameter were

[149] We also triangulated this figure against Beauhurst report on Fail, Scale and Exit rates in the UK (2022) which suggests that c. 20% of high growth innovative companies fail within five years, only 23% scale up and c. 55% stagnate.

[150] The distributions were truncated to match the survey data. Specifically no negative values for turnover uplift were allowed, and the annual turnover uplift was capped at £10m for leads and £5m for collaborators. We note however, that these caps have little influence on overall results because outcomes of that scale are rare.

Parameter	Value	Source/evidence/comments
		triangulated from responses to questions about realised and expected turnover (over the next three years)
Further parameters needed to arrive to present value of net additional turnover		
Discount rate	3.5%	In line with the Green Book guidance all expected values were discounted
Displacement	25%	Displacement occurs when an increase in economic activity due to TFP support reduces economic activity of non-beneficiaries in the UK. This parameter was determined based on survey responses of beneficiaries to the question about expected levels of competition they may face

Source: SQW

G.3 **The model was also calibrated for internal consistency.** For example, we checked that the number of projects predicted by the model to commercialise over the next three years based on their starting TRL is consistent with expectations of survey respondents; and that the assumptions in relation to the distribution of the number of collaborators per project result in the total number of business beneficiaries that is in line with monitoring data.

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