Routes to Reduce Methane Emissions from Livestock Systems

Prof Carol-Anne Duthie, Prof Eileen Wall, Prof Rainer Roehe, Dr Gemma Miller, Dr Nicola Lambe, Prof John Newbold

Policy Summary

This report identifies the options for reducing methane emissions from beef, sheep and dairy livestock sectors, their current readiness level and potential to deliver emissions reductions, the timescales, costs, and co-benefits to implementation.

Each methane mitigation measure was scored from 1-9 (1 being at a conceptual or initial stage and 9 being complete/ready) across five categories:

1. Technology
2. User
3. Market
4. Societal
5. Regulatory

Scores were averaged across these five categories and the measures were ranked by averaged TRL for the beef, dairy and sheep sectors separately.

Key points:

- For beef, sheep, and dairy sectors 'Forage adjustment – clovers and lucerne (alfalfa)', 'Forage adjustment – grass improvement - high sugar varieties', and 'Forage adjustment – maize and whole crop cereal silages' ranked within the highest averaged TRL (8) and were the only technologies that scored 8 for the sheep sector. However, the evidence shows only small reductions in methane are achievable, or the need for further research.
- For the beef and dairy sectors, national genetic evaluations for production and feed efficiency, breeding for feed efficiency and use of sex semen are well established in dairy (TRL 8), the methodology to breed for feed efficiency exists for the beef and sheep sectors but with limited uptake due to costs involved in measuring feed intake and low use of artificial insemination (AI, which also limits use of sexed semen).
- Methane reducing feed supplements are at various levels of readiness but are all limited by a lack of clear improvement in performance and no other incentives for their use.
- Breeding for methane emissions is limited by the cost of equipment to measure methane (e.g. respiration chambers and greenfeeds). The use of portable accumulation chambers (PACs) is expected to accelerate selective breeding for reduced methane emissions in sheep. Microbiome driven breeding may emerge as a better option for beef and dairy than breeding based on direct measurements of methane.

- Direct air capture methods (GreenShed and halter devices) are at an early stage of development.

This report considers the implementation of these mitigation measures in isolation. When more than one measure is put into effect there will be an interaction between them, and so emissions reductions will not necessarily be cumulative. Interactions between mitigation measures have not been widely studied.

Contents

Introduction

The agricultural sector has only achieved a 10.8% reduction in greenhouse gas (GHG) emissions since the baseline year of 1990 (Scottish Greenhouse Gas Statistics, 2021). To meet the Scottish Government's target of Net Zero emissions by 2045 reform is required in the agricultural sector to drive down emissions.

Methane is the prominent GHG from agriculture, accounting for 59% of agricultural emissions. Agriculture contributed to 45% of Scotland's total methane emissions in 2021. Enteric methane, produced by ruminants as they digest feed, was the major source. There are several options to reduce enteric methane emissions, some of which could deliver reductions in the short to medium term (e.g. dietary), and some of which are considered longer-term strategies (e.g., breeding). Note that although measures to improve animal health are important, they are not included in this report as they only indirectly lead to reductions in methane emissions (e.g., avoidance of reduced performance caused by an incidence of disease).

The objective of this report is to provide evidence to support policy development for agricultural reform and climate change plan targets. The report identifies the menu of options for reducing methane emissions from beef, sheep and dairy livestock sectors, their current readiness and potential to deliver emissions reductions, the timescales, costs, and co-benefits to implementation. The outcome will be clarity on the current readiness and potential capability of each different technology to reduce methane emissions, alongside costs and co-benefits.

Completed tasks:

(i) Table 1. Reporting readiness levels, potential impact at balanced readiness level 8 (% reductions in emissions), costs and co-benefits, and estimated time to achieve readiness at level 8.

(ii) Succinct supporting report providing: (a) an overview of potential technologies in Annex 1; (b) a brief justification of the readiness assessment, potential impact, costs, and benefits reported in the table; and (c) for each sector a ranking of the technologies by overall readiness and by overall potential impact at readiness level 8.

List of Acronyms

3-NOP - 3-nitrooxypropanol
AI – artificial insemination
ARL – acceptance readiness level
CH_4 – methane
CO_2 – carbon dioxide
CO_2eq – carbon dioxide equivalents
DMI – dry matter intake
MRL – market readiness level
ORL – organizational readiness level
PAC – portable accumulation chamber
RFI – residual feed intake
RL – readiness level
RoI – return on investment
RRL – regulatory readiness level
TRL – technological readiness level

SECTION 1. READINESS LEVELS, POTENTIAL IMPACT AT BALANCED READINESS LEVEL 8 (% REDUCTIONS IN EMISSIONS), COSTS AND CO-BENEFITS, AND ESTIMATED TIME TO ACHIEVE READINESS AT LEVEL 8

Framework adopted from Vik et al., 2021[a]

Level	TRL «Development»	MRL «Commodification»	RRL «Legalization»	ARL «legitimization»	ORL «domestication»
1	Specific technological idea is formulated	Hunch of a market need	The legal and/or regulatory aspects of the technology is unpredictable or unknown or unpredictable	The technology is or will be seen as illegitimate or unacceptable	The technology represents a fundamental break with existing work processes or organizing
2	The technology idea is explicitly described	Market and product are described	Use or production will require changes of laws.	The technology will be seen as controversial in large parts of the population	Unclear how the technology might be adapted to existing work processes/organization
3	Experimental proof of concept	Market need and market supply are explicated.	Use and/or production will require change or reinterpretations of regulatory framework	The technology is seen as unwanted or inappropriate among groups of the population	An idea about integration domestication exist
4	Technological elements are tested and validated in lab or simulated environment	Validation of market/small pilot campaign	Use and/or production will require demanding permissions or approvals	The technology is seen as controversial among groups of the population	Integration with work processes/organization is formulated
5	Integrated technology tested and validated in lab or simulated environment	Business model described	Use and/or production will presuppose accessible permissions or approvals	Use of the technology is seen as unwanted or inappropriate among key actors in the sector	A concrete plan for integration with existing work processes is formulated
6	Technology demonstrated in relevant environment	Products are being launched in limited scope	Necessary approvals are likely	Use of the technology is seen as unwanted or inappropriate among a few actors in the sector	Large/fundamental organizational changes are needed in order to use the technology
7	System prototype demonstrated in natural environment	Customers confirm progress/improvement	Necessary approvals for use or production are "just around the corner"	The technology is seen as controversial in parts of the sector	Small organizational changes are needed in order to use the technology
8	Product tested and validated, and the functionality is being optimized	Stable sale makes income predictions possible	Use or production fulfill general conditions	The technology is seen as controversial among marginal interest groups	Technology is adapted to work processes and/or existing technology
9	Actual system proven functional in natural environment	Market confirms stability/growth	Use and production are regulatory unproblematic	The technology is generally accepted/applauded	The technology works seamlessly with existing technology

[a] Vik, J,. Melas, A.M., Straete, E.P., Soraa, R.A., 2021. Balanced readiness level assessment (BRLa): A tool for exploring new and emerging technologies. Technological Forecasting and Social Change, 169, 120854.

Table 1. Readiness levels, emissions reduction, time to reach RL8, co-benefits and costs.

Innov. No.	Innovation	Sector	Current readiness levels (1-9)					Emissions reduction at average RL= 8		Time to reach average RL 8 (years)	Co-benefits	Costs
			Technology	User	Market	Societal	Regulatory	Per animal per day (%)	Per unit production (%)			
1a	Feed supplements: Bovaer 10	Beef	8	8	3	4	6	~32%	-27%	3	Possible minor improvement in feed conversion efficiency	Unknown
1b	Feed supplements: Bovaer 10	Sheep	6	8	3	4	6	~33%	~34%	3	Unknown	Unknown
1c	Feed supplements: Bovaer 10	Dairy	8	8	3	4	7	~33%	~33%	<1	Possible minor increase in milk fat and protein concentration	Unknown
2a	Feed supplements: Agolin Ruminant	Beef	6	8	3	9	4	~10%	~10%	3	Potential improvement in feed efficiency	Approx. £0.02 / animal / day

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	Innovation	Sector	Technology	User	Market	Societal	Regulatory	Per animal per day (%)	Per unit production (%)	Time to reach average RL 8 (years)	Co-benefits	Costs
2b	Feed supplements: Agolin Ruminant	Sheep	5	8	3	9	4	No information	2	5	Unknown	
2c	Feed supplements: Agolin Ruminant	Dairy	6	8	3	9	4	~9%	~16%	3	Potential increase in milk yield (3.6%)	Approx. £0.04 / animal / day
3a	Feed supplements: Silvair	Beef	8	8	6	2	9	~11%	~7%	2	None	Unknown
3b	Feed supplements: Silvair	Sheep	2	8	2	2	9	~14%	~26%	5	None	Unknown
3c	Feed supplements: Silvair	Dairy	8	8	6	2	9	~22%	~18%	2	None	€0.10 to €0.15/cow/day

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	Innovation	Sector	Technology	User	Market	Societal	Regulatory	Per animal per day (%)	Per unit production (%)	Time to reach average RL 8 (years)	Co-benefits	Costs
4a	Feed supplements: Red seaweed (Asparagopsis)	Beef	6	8	2	7	9	65%	56%	5	None	Unknown
4b	Feed supplements: Red seaweed (Asparagopsis)	Sheep	6	8	2	7	9	~53%	~53%	5	None	Unknown
4c	Feed supplements: Red seaweed (Asparagopsis)	Dairy	5	8	2	7	9	~35%	~22%	5	None	Unknown
5a	Feed supplements: Enterix	Beef	6	8	6	7	9	~12%	~7%	3	None	Unknown
5b	Feed supplements: Enterix	Sheep	5	8	6	7	9	~8%	~9%	5	None	Unknown

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
5c	Feed supplements: Enterix	Dairy	7	8	6	7	9	~23%	~24%	1	Potential increase in milk yield (5-8%)	Unknown
6a	Breeding for feed conversion efficiency (within breeds and/or commercial breeding companies)	Beef	8	6	6	8	8	Annually 0.75% to 1% CH_4, cumulative	Annually 0.75% to 1% CH_4, per kg beef, cumulative	6	Decreasing costs of production	Feed intake recording costs need an appropriate return
6b	National genetic evaluations for production and feed efficiency	Beef	8	6	7	8	9	1-1.5% CH_4/yr, cumulative	2-3% CH_4/kg beef/yr, cumulative	1-2 generations (8-10 years), could be faster with genomics (3-6 years)	Reduced time to finish (60-90 days), reduction in feed costs, optimising feed conversion on current/future diets	Model for national systems estimated at £200k-£250k/yr (and potentially /breed). depending on other population drivers/initiatives (e.g., mixed breed genomics, beef from dairy etc) costs could be optimised for RoI

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
6c	Breeding for feed conversion efficiency	Sheep	7	6	4	6	8	~0.5-2% per annum cumulative	1-2% per annum cumulative	6	Increased production efficiency, reduced inputs	Indoor housing & feeding required. Expensive phenotype per animal (current estimate ~£300 per lamb).
6d	National genetic evaluations feed efficiency	Dairy	8	8	8	8	9	1% CH4/yr, cumulative	1.5-2% CH4/kg milk solids/yr, cumulative	Immediate. Methane reduction impacts expected 1-2 generations (2-4 years) for progeny to enter the milking herd.	Reduction in feed costs, optimising feed conversion on current/future diets, potential cross over benefit for dairy-beef if integrated	Genomics for feed efficiency nationally available from research records. Routinely ground truth and re-prediction required at industry level Similar to beef per breed but likely better starting infrastructure working with industry recording (£150k-£200k/yr to generate population relevant feed intake and production records). Potential savings/cost sharing through dairy-beef efficiency.

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
6e	Breeding for feed efficiency (within commercial breeding companies)	Dairy	7	7	7	8	9	1% CH4/yr, cumulative	1.5-2% CH4/kg milk solids/yr, cumulative	2-3 generations (4-6 years)	Reduction in feed costs, optimising feed conversion on current/future diets	Similar to beef per breed but likely better starting infrastructure working with industry recording (£150k-£200k/yr to generate population relevant feed intake and production records).
7a	Breeding for methane mitigation using respiration chamber measurements	Beef	5	3	3	7	5	Annually 2% to 5% CH4, cumulative	Annually 2% to 5% CH4 per kg beef, cumulative	n/a		Respiration chamber measurements are too costly for large-scale breeding
7b	Breeding for reduced methane emissions	Sheep	8	5	4	6	5	~1-3% per annum cumulative (7.5% p.a. over 20yrs)	~1-3% per annum cumulative	3	Maintaining genetic progress in maternal & production traits. Targets grass-based systems.	Requires transport of equipment around the country. Cost per PAC phenotype in the range £40-100 per animal.

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7c	Breeding for reduced methane emissions	Dairy	7	7	6	7	7	0.5%- 1% CH_4/yr, cumulative (additional to feed efficiency saving)	1-1.5% CH_4/kg milk solids/yr, cumulative	1-2 generations (2-4 years)	High correlation with feed efficiency so potential correlated savings in feed efficiency if not already in the breeding goal (which is in the UK goal)	Generating population relevant direct measures of methane expensive through chambers but there is field deployable kit (e.g., GreenFeeds) being used. Estimated cost of £500k/yr in first 3-5 yrs instance to establish dataset and annual cost of £250k to maintain dataset.
8a	Microbiome-driven breeding for methane mitigation	Beef	7	7	6	7	7	Annually 3% to 7% CH_4, cumulative	Annually 3% to 7% CH_4per kg beef, cumulative	4	Feed efficiency, animal health, meat quality, etc.	10% to 30% higher cost for semen
8b	Microbiome-driven breeding for methane mitigation	Sheep	5	4	5	4	5	1-3% per annum cumulative	1-2% per annum, cumulative	10	Feed efficiency, animal health, meat quality, etc.	Implementation cost and running cost. Lab cost per phenotype estimated in the range £40-60 per animal.

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
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8c	Microbiome-driven breeding for methane mitigation	Dairy	5	7	5	7	7	Annually 3% to 7% CH_4, cumulative	Annually 3% to 7% CH_4per kg milk, cumulative	6	Feed efficiency, animal health, meat quality, etc.	10% to 30% higher cost for semen
9a	Sexed semen	Beef	7	6	6	8	8	10-20% (differs for suckler and finishing beef)	10%/kg meat	5 (need adoption of AI)	Males grow faster. Faster genetic progress with broader use of AI in beef	AI rates in beef low, sexed semen more expensive, breeding companies sexing beef bulls required.
9b	Sexed semen	Sheep	2	1	1	6	4	10-20% (should theoretically mirror beef)	10%/kg meat	10	Males grow faster. Faster genetic progress with broader use of AI	AI more difficult in sheep and systems not set up. Value of animal is such that unlikely to be an effective solution
9c	Sexed semen	Dairy	9	7	8	8	8	20-25%	10%/kg milk	0 (already deployed)	Reduces surplus male dairy calves, targeted sexed dairy and beef semen into dairy cows could have wider benefits if suckler herd shrank	Costs of sexed semen to farmer. Wider population benefits (changing the herd structure) to maximise benefit would require support.

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
10a	CH_4 direct air capture - GreenSheds	Beef	5	7	5	4	6	Yet to be quantified. Initial calculations suggest: 222tCo2eq removal per shed / annum – housing 100 finishing animals (~60% over the animals lifetime)	Unknown	5-10	Economic (new product output, beef sales premium); Circularity; Production of low carbon fertiliser	~£400k investment for 100 animal shed; 7-8 yr ROI with govt incentivisation; business case being developed in more detail.
10b	CH_4 direct air capture - GreenSheds	Sheep	2	6	2	2	6	Unknown	Unknown	Unlikely	Not explored.	Not explored.

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
10c	CH_4 direct air capture – GreenSheds	Dairy	3	7	2	4	6	Unknown	Unknown	10	Economic (new product output, beef sales premium); Circularity; Production of low carbon fertiliser	Not yet explored for dairy buildings
11a	CH_4 direct air capture – halters	Beef	5	7	2	4	9	No data	No data	>10 years	Potential benefits associated with increased automated monitoring of individual animals. From the ZELP website: 'We track activity, temperature, rumination and feed to identify potential signals of disease…'.	Unknown

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
11c	CH_4 direct air capture - halters	Dairy	5	7	2	4	9	No data	No data	>10 years	Potential benefits associated with increased automated monitoring of individual animals. From the ZELP website: 'We track activity, temperature, rumination and feed to identify potential signals of disease…'.	Unknown
12a	Forage adjustment – grass improvement - high sugar varieties	Beef	6	9	6	9	9	Insufficient data	Insufficient data	2	Improved Nitrogen Use Efficiency	Negligible versus conventional grass

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
12b	Forage adjustment – grass improvement - high sugar varieties	Sheep	6	9	6	9	9	Insufficient data	Insufficient data	2	Improved Nitrogen Use Efficiency	Negligible versus conventional grass
12c	Forage adjustment – grass improvement - high sugar varieties	Dairy	6	9	6	9	9	Insufficient data	Insufficient data	2	Improved Nitrogen Use Efficiency	Negligible versus conventional grass
13a	Forage adjustment – grass improvement - high lipid grass	Beef	4	7	4	2	2	ca. 30 (potential)	Not known	5-10	Productivity	Not known

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
13b	Forage adjustment – grass improvement - high lipid grass	Sheep	4	7	4	2	2	ca. 30 (potential)	Not known	5-10	Productivity	Not known
13c	Forage adjustment – grass improvement - high lipid grass	Dairy	4	7	4	2	2	ca. 30 (potential)	Not known	5-10	Productivity	Not known
14a	Forage adjustment – maize and whole crop cereal silages	Beef	7/8	9	6	8	9	0	5	0	Productivity. Nitrogen Use Efficiency.	Negligible.

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
14b	Forage adjustment – maize and whole crop cereal silages	Sheep	7/8	9	6	8	9	0	5	0	Productivity. Nitrogen Use Efficiency.	Negligible.
14c	Forage adjustment – maize and whole crop cereal silages	Dairy	7/8	9	6	8	9	0	5	0	Productivity. Nitrogen Use Efficiency.	Negligible.
15a	Forage adjustment – clovers and lucerne (alfalfa)	Beef	7	9	6	9	9	0	0	2	Saving cost and carbon through reduced need for inorganic N fertiliser. Biodiversity gain.	Negligible.

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
15b	Forage adjustment – clovers and lucerne (alfalfa)	Sheep	7	9	6	9	9	0	0	2	Saving cost and carbon through reduced need for inorganic N fertiliser. Biodiversity gain.	Negligible.
15c	Forage adjustment – clovers and lucerne (alfalfa)	Dairy	7	9	6	9	9	0	0	2	Saving cost and carbon through reduced need for inorganic N fertiliser. Biodiversity gain.	Negligible.
16a	Forage adjustment – multispecies swards ('herbal leys')	Beef	6	7	6	9	9	0-15	0-10	3	Less reliance on inorganic N fertiliser, drought resistance, healthier soils, potentially improved animal health, biodiversity and other ecosystem services	2x/ha versus grass

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
16b	Forage adjustment – multispecies swards ('herbal leys')	Sheep	6	7	6	9	9	0-15	0-10	3	Less reliance on inorganic N fertiliser, drought resistance, healthier soils, potentially improved animal health, biodiversity, and other ecosystem services	2x/ha versus grass
16c	Forage adjustment – multispecies swards ('herbal leys')	Dairy	6	7	6	9	9	0-15	0-10	3	Less reliance on inorganic N fertiliser, drought resistance, healthier soils, potentially improved animal health, biodiversity, and other ecosystem services	2x/ha versus grass
17a	Forage adjustment - forage brassicas	Beef	6/7	6	6	8	9	15-20	Not known	2	Productivity	

			Current readiness levels (1-9)					Emissions reduction at average RL= 8				
Innov. No.	**Innovation**	**Sector**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Per animal per day (%)**	**Per unit production (%)**	**Time to reach average RL 8 (years)**	**Co-benefits**	**Costs**
17b	Forage adjustment – forage brassicas	Sheep	6/7	6	6	8	9	15-20	Not known	2	Productivity	
17c	Forage adjustment – forage brassicas	Dairy	6/7	6	6	8	9	15-20	Not known	2	Productivity	
18a	Forage adjustment: Management Intensive Grazing	Dairy	4-8	5-7	4-7	5-7	3-8	Poorly quantified	Poorly quantified		Productivity	Variable

SECTION 2. TECHNOLOGY OVERVIEW

1. Feed supplements

'Feed supplement' is used here as a neutral term to include products regulated as Feed Additives and products regulated as Feed Materials. This distinction influences Readiness level, with significantly more time and investment needed to secure authorisation as a zootechnical Feed Additive than as a Feed Material.

We have assessed the Readiness of Feed Supplements *for use as methane mitigators*, including necessary authorisations. Products may have different Readiness Levels for other purposes (for example, Agolin Ruminant has a lower Readiness Level as a methane mitigator than as a sensory product, due partly to its current regulatory status).

For additional background information, a report collating the information used in evaluating the feed supplements discussed here is Miller et. al., (2023, doi: 10.58073/SRUC.24807618)

1a-c. Feed supplement (Feed Additive): Bovaer 10

- **Technology -** Bovaer is the trademark name for 3-nitrooxypropanol (3-NOP) manufactured by DSM Nutritional Products Ltd. Bovaer is a small synthetic molecule which inhibits methane production directly by inhibiting the enzyme methyl-coenzyme M reductase which catalyses methane synthesis by archaea.
- **User -** Bovaer is currently recommended for use in pre-mixes to ensure dosage is coupled to feed intake. Therefore, the product can easily be incorporated into many existing indoor production systems. Dosage levels are small (60-90mg 3-NOP per kg dry matter intake) and so development of slow-release boluses and/or lick tubs or blocks for use with grazing animals may be possible. Slow-release formulations are currently being tested.
- **Market –** Bovaer is not yet freely available in the GB market. There are currently few direct incentives for producers to use feed supplements for methane reduction. Market pull from retailers, food manufacturers and consumers for low-methane milk and red meat may drive uptake.
- **Societal –** Consumers may not be comfortable with synthetic chemicals being fed to animals producing food for human consumption. Bovaer has no known health or welfare implications for animals or to humans consuming animal products. Concerns have been voiced about possible effects on emissions from manure, and possible effects of manure from animals fed 3-NOP on soils. While some work has been conducted in Canada, further research is warranted.

- **Regulatory –** The product is authorised as a 'zootechnical feed additive with a favourable effect on the environment' for use with 'dairy cows and cows for reproduction' in the EU (and Northern Ireland) and Great Britain.
- **ER / animal / day or per kg DMI –** The methane reduction potentials given here are based on simple averages of efficacy in published literature or (for dairy) a recent meta-analysis (Krebreab et al., 2023). Some studies have shown methane reductions of >80% under specific conditions. There is extensive evidence supporting the efficacy of Bovaer for dairy and beef cattle, but only limited evident for sheep (one study). All studies were conducted in indoor production systems, so potential usage with grazing animals is unproven.
- **Time to reach average RL 8 –** Uptake of the product will depend on incentives for farmers and on the perception of consumers. Use in grazing ruminants will depend on the development of technologies to deliver 3-NOP to the rumen (e.g., slow-release product formulations). Consumers have indicated a preference for the use of 'natural' products (Duthie et al., 2022).
- **Co-Benefits –** Reported effects on animal productivity are small, with reports of increased milk fat and protein concentration in some dairy studies and improved feed conversion efficiency in some beef cattle studies.
- **Cost –** Costs of this product are currently unknown.

2a-c. Feed supplement (Feed Additives): Agolin Ruminant

- **Technology –** Agolin Ruminant is a proprietary blend of essential oils, with the main active components being coriander seed oil, eugenol, geranyl acetate, and geraniol.
- **User –** The product is designed to be incorporated into premixes and this is how it is sold in the UK. Therefore, the product can easily be incorporated into existing indoor production systems. The high dosage required prohibits its direct use with grazing animals and the volatile nature of the essential oil ingredients will likely limit the range of feed products into which it can be incorporated.
- **Market –** The product is on the UK market but is sold by the distributor under a different brand name. There are currently no incentives for producers to use the product for methane mitigation. Market pull from retailers and consumers for low-methane milk and red meat may drive uptake.
- **Societal –** Products perceived to be natural are readily accepted by consumers. Agolin Ruminant has no known health or welfare implications for animals or to humans consuming animal products.
- **Regulatory –** The essential oil ingredients in Agolin Ruminant are currently approved as sensory feed additives in the EU and UK. They are not authorised for sale as zootechnical feed additives 'which favourably affect the environment'.

- **ER / animal / day or per kg DMI -** There is only limited published evidence for the efficacy of Agolin Ruminant in reducing enteric methane (three papers studying dairy, and one studying beef). There is some evidence that it takes several weeks for the product to become effective, so longer-term studies are required to study how animals adapt. The average reductions given here are based on simple averages from the available evidence.
- **Time to reach average RL 8 –** Already at RL8 for dairy and beef as a sensory feed additive (flavour). Lower RL as a methane mitigator as not authorised for this purpose. More in vivo measurements of the effect on methane reduction would strengthen confidence. This product has not been tested on sheep and is not marketed for sheep.
- **Co-Benefits –** A meta-analysis found a small increase in milk yield in dairy cows supplemented with Agolin Ruminant (+3.6%, Belanche et al., 2020).
- **Cost -** In the UK, Agolin Ruminant costs approximately £0.04/animal/day for dairy cows and £0.02/animal/d for beef cattle (personal communication from UK distributor).

3a-c. Feed supplement (Feed Material): Silvair

- **Technology -** SilvAir is Cargill's trademark name for the inorganic salt calcium nitrate (specifically, 'Calcium nitrate double salt', 5 Ca (NO3)2 x NH4NO3x10 H2O).
- **User -** There is a risk of nitrate poisoning if the rumen is not adapted and if an excessive amount of nitrate is consumed. For this reason, the product is currently only offered in a pelleted form. This restricts its usage to housed cattle only. The product could easily be integrated into indoor production systems.
- **Market –** SilvAir is not yet available in the UK. There are currently no incentives for producers to use feed supplements for methane reduction. Market pull from retailers and consumers for low-methane milk and red meat may drive uptake.
- **Societal –** Consumers may not be comfortable with synthetic chemicals being fed to animals producing food for human consumption (although nitrate, at low levels, is naturally present in fresh forages).
- **Regulatory -** Calcium nitrate double salt is a Feed Material (a source of calcium and an alternative to urea as a source of non-protein nitrogen). Note that no other form of nitrate is included in the EU Catalogue of Feed Materials.
- **ER / animal / day or per kg DMI -** There is a substantial evidence base supporting the efficacy of calcium nitrate for methane reduction in dairy and beef, but only one published study on sheep. The average reductions given here are based on simple averages from the available evidence.

- **Time to reach average RL 8 –** Uptake of the product will depend on incentives for farmers and on the perception of consumers. Consumers have indicated a preference for the use of 'natural' products (Duthie et al., 2022).
- **Co-Benefits –** No specific effects on animal productivity. Can displace other sources of N and Ca in diets.
- **Cost –** It is expected that SilvAir will be placed on the European market at €750/tonne, (approximately €0.25/cow/day - personal communication from manufacturer). This is a gross cost: as the product contains nitrogen and calcium, it will replace some of the protein and calcium ingredients in compound feeds, resulting in formulation savings. The amount saved will depend on the raw materials replaced and their costs but is expected to reduce the net cost to approximately €0.10 to €0.15/cow/day.

4a-c. Feed supplements (Feed Material): Asparagopsis meal

This section appraises Asparagopsis meal (a Feed Material). Products derived from Asparagopsis are thought to be in development (e.g. oil extractions). These would likely require authorisation as Feed Additives and are not evaluated here.

- **Technology -** Asparagopsis is a genus of red macroalgae widely found in tropical to warm marine waters. It contains halogenated methane analogues with bioactive properties, the most abundant of which is bromoform (CHBr3). Bromoform directly inhibits methane production by inhibiting the cobamide-dependent enzyme methyl-coenzyme (CoM) reductase step in methanogenesis.
- **User -** Asparagopsis is currently offered to animals as seaweed meal (dried and ground). In this form the product can easily be integrated into current indoor production systems. Use in grazing animals would be difficult as the dosage level is too high for slow-release boluses, but incorporation into a mineral lick may be possible. Oil extracts are being evaluated as alternatives to simple asparagopsis meal.
- **Market –** Asparagopsis is not yet available on the UK market. As a seaweed species native to warm and temperate waters, the product would need to be imported or grown in artificial environments. Asparagopsis as a feed ingredient for livestock is patented by FutureFeed Pty Ltd (Newstead, Australia), who deliver supply chain access to Asparagopsis growers through licence agreements. There are currently no incentives for producers to use feed supplements for methane reduction. Market pull from retailers and consumers for low-methane milk and red meat may drive uptake.
- **Societal –** Products perceived to be natural are readily accepted by consumers. There are issues around bioaccumulation of micronutrients such as arsenic, lead

and iodine which can reach levels where they cause toxicity. for example, iodine concentrations may reach levels where you could not feed enough seaweed to meet the methane reduction potential without causing iodine toxicity. Additionally, Asparagopsis contains bromoform which is a potential carcinogen and may be passed into meat and milk intended for human consumption.

- **Regulatory –** Asparagopsis, simply dried and ground, is described by a separate entry in the latest EU Catalogue of Feed Materials (EC Regulation 1104/2022, entry 7.1.7, '*Algae meal from Asparagopsis*', described as '*Product obtained by drying and crushing macro-algae of the genus Asparagopsis. May be washed to reduce iodine and bromine content.*' In practice, incorporation of Asparagopsis into ruminant diets may be limited by legislation on iodine. EC Regulation 2015/861 sets upper limits for iodine at 5mg/kg complete feed and 10mg/kg complete feed for dairy and beef cattle, respectively (with the lower limit for dairy driven by concerns over transfer to milk). Oil extractions of Asparagopsis (to concentrate bromoform and reduce concentrations of iodine and bromine) would likely be required to seek authorisation as zootechnical Feed Additives.
- **ER / animal / day or per kg DMI -** There is only limited evidence for the efficacy of Asparagopsis meal in vivo. Although some studies have found large reductions (>90%), these high reductions appear to be only under specific conditions.
- **Time to reach average RL 8 –** This will depend on the development of a sufficient and consistent supply chain to the UK market. More in vivo evidence is required to understand the variability in methane reduction between different production systems. Incentives will likely be required to encourage up-take.
- **Co-Benefits -** There is some limited evidence that milk yield may decrease (e.g., Stefanoni et al., 2021)
- **Cost -** Costs of this product are currently unknown.

5a-c. Feed supplement (Feed Material and Feed Additive): Enterix

- **Technology –** Formerly known as Mootral Ruminant, Enterix is a pelleted feed containing a proprietary blend of garlic powder (a Feed Material) and citrus extract (a Feed Additive). Garlic contains several bioactive compounds, including alliin, diallyl sulfides, and allicin which have anti-microbial properties, and citrus extract contains flavonoids which may have methane reducing properties. Enterix is currently only available in the UK through a Verra certified carbon credit project (UK CowCredit Project).
- **User –** The product is currently supplied in a pelleted form, which can easily be incorporated into existing indoor production systems. The volatile nature of the essential oil ingredients will likely limit the range of feed products into which it can be incorporated.

- **Market –** Enterix (manufactured by Mootral) is currently available to a small number of dairy farms through a Verra certified carbon credit ('UK Cow Credit' project).
- **Societal –** Products perceived to be natural are readily accepted by consumers. Enterix has no known health or welfare implications for animals or to humans consuming animal products.
- **Regulatory –** The active ingredients in Enterix are Feed Materials ('garlic, dried', entry 4.5.1. in the EU Catalogue of Feed Materials, EC Regulation 1104/2022) or sensory Feed Additives (citrus extract) in the EU and UK. Therefore, no claim for methane mitigation due to citrus extract can be made.
- **ER / animal / day or per kg DMI –** There is a lack of in vivo evidence on the efficacy of Enterix for the reduction of methane production with only five published studies (two in dairy, one beef and one sheep). The average reductions given here are based on simple averages from the available evidence. Note: since preparing this report, a further study of Enterix in dairy cows has been reported. This confirms reductions in methane production (g/d), yield (g/kg DMI) and intensity (g/kg milk), but of a lower magnitude (-10%) than in some previous studies.
- **Time to reach average RL 8 –** Uptake of the product will depend on incentives for farmers. More in vivo evidence of efficacy would strengthen confidence.
- **Co-Benefits –** There is some limited evidence that Enterix may increase milk yield from dairy cows (Vrancken et al., 2019). Other studies show no effect on milk yield or composition.
- **Cost –** Costs of this product are currently unknown.

6a. Breeding for feed conversion efficiency (within breeds and/or commercial breeding companies) - beef

- **Technology –** The methodologies for breeding of feed conversion efficiency in beef have been developed whereby the most common used method is based on residual feed intake. Residual feed intake is the difference between measured feed intake and the expected feed intake predicted based on the cattle's growth rate, body composition and maintenance requirements. This methodology allows for improved feed conversion efficiency independent from growth rate, body composition and the maintenance requirement of cattle. The main challenge of a meaningful improvement of feed conversion efficiency in beef cattle is the high cost involved in large scale recording of feed intake. There are electronic systems for recording feed intake available, but they are costly and require cattle to be housed indoors. Therefore, methodologies for which no large-scale measurements of feed intake are required, such as microbiome-driven breeding (as explained in detail in section 8a&c), provide opportunities to estimate the genetic merit of cattle for improvement of feed conversion efficiency. Simultaneously, with this breeding strategy methane emissions per day can be mitigated as described in detail in section 8a&c (Martínez-Álvaro et al., 2022). Microbiome-driven breeding is more cost-effective than selection based on residual feed intake for which measured feed intake measurements are needed at large scale. The technology of residual feed intake for genetic evaluation of feed conversion efficiency is available and has been proven. For microbiome-driven breeding, the assessment is provided for beef cattle in a separate section of this report (see section 8a&c).

- **User –** Breeding organisations have a limited uptake of accurate selection for feed conversion efficiency due to high cost of recording feed intake and the low use of AI in beef herds.
- **Market – T**he market for accurate selection for feed conversion efficiency based on appropriate large-scale recording of feed intake is limited due to high cost of recording feed intake.
- **Societal –** Improvement of feed conversion efficiency is seen as controversial among marginal interest groups, e.g., rare breeds will probably not have the population size and logistics to achieve sufficient recording of feed intake.
- **Regulatory –** The use of breeding for feed efficiency is regulatory unproblematic.
- **Annual mitigation of methane emissions (%) –** Basarab et al. (2013) reported that selection for residual feed intake will reduce enteric methane emissions by 0.75% to 1.0% per year. Using microbiome-driven breeding the prediction of residual feed intake could be cost-effectively extended on a larger population and thus estimated with higher accuracy resulting in higher reduction in GHG emissions.
- **Time to reach average RL 8 –** The time of implementation of accurate selection for feed efficiency based on large scale recording of feed intake depends most likely on incentives given for farmer using AI and the use of semen from bulls inheriting improved feed efficiency to their progeny. This would attract breeding organisations to implement large scale recording of feed intake. Therefore, the time of implementation depends not on the technology but on the economics allowing for large scale recording of feed intake.
- **Co-benefits –** Besides the reduction in GHG emissions per kg product due to improvement of feed conversion efficiency, the cost of production will decrease to improve the sustainability of beef production.
- **Costs –** The high cost associated with recording feed intake and the low level of artificial inseminations (AI) is hampering the implementation of selection for feed conversion efficiency in beef herds. For beef from dairy herds, some breeding organisations can recover these costs due to the high demand for semen from beef bulls because of the successful uptake of sexed semen for breeding dairy replacements.

6b. National genetic evaluations for production and feed efficiency – beef

- **Technology** - The National Genetic Evaluations for production and feed efficiency in beef cattle, as supported by AHDB, represent an innovative solution to the beef industry's challenges. This system, operating both at multi- and cross-breed levels, evaluates the genetic potential of cattle, pinpointing those with superior traits for producing beef efficiently[1]. Furthermore, with the support of Defra, the Scottish Government, and the broader beef industry, a dedicated national feed intake resource and system have been established. This system meticulously records feed efficiency in commercial settings but is governed by a preset blueprint. The synergy of genetics and rigorous feed intake recording promises not only higher production efficiency but also a significant reduction in methane emissions, addressing a critical environmental concern tied to beef production[2]. The research and genetic and genomic evaluation systems have been developed and could provide a platform for building on to ensure available into the future and for all farmers. (TRL:8)
- **User**: Farmers (beef and dairy), beef cattle breeders, and pedigree herds involved in performance recording are the primary beneficiaries. These stakeholders will utilise the evaluations and the resources provided to optimise their breeding and feeding practices. However current uptake of these tools is low in beef and hampered also by a low rate of artificial insemination which slows down dissemination of genetic improvement (URL: 6)
- **Market:** The UK beef industry stands to gain considerably, from improved efficiencies in the production system. With enhanced feed efficiency, there could also be potential ramifications on the animal feed market, altering consumption and production dynamics. (MRL: 7)
- **Societal:** Societal benefits extend beyond just beef production. Addressing global concerns about greenhouse gas emissions, this technology offers a more sustainable and environmentally conscious method of beef production. The ripple effect might also influence beef prices and market dynamics. (SRL: 8)
- **Regulatory:** There are no regulatory blocks to the technology at present and is already in use**.** Regulatory entities like Defra and the Scottish Government are evidently supportive, given their involvement in developing resources and systems. They might introduce or have in place incentives, regulations, or

[1] https://ahdb.org.uk/knowledge-library/national-beef-evaluations
[2] https://ahdb.org.uk/beef-feed-efficiency-programme

frameworks that foster the adoption of these evaluations to achieve both industry efficiency and environmental sustainability. (RRL: 9)

- **Annual mitigation of methane emissions (%):** The technology's deployment could see a cumulative annual reduction of methane emissions by 1-1.5% CH_4.[3]
- **Annual mitigation per unit of production (%):** When broken down per unit, the figures are even more promising with a 2-3% CH_4 reduction for each kilogram of beef produced yearly, on a cumulative basis.
- **Time to reach average RL 8:** Though conventional breeding techniques might take 8-10 years to realise widespread adoption, leveraging modern genomic tools could significantly accelerate this, potentially delivering results within 3-6 years.
- **Co-benefits:**
    1. A reduction in cattle finishing time, estimated at 60-90 days.
    2. Notable feed cost reductions.
    3. Refined feed conversion metrics, ensuring adaptability to both present and future diet compositions.
- **Costs:** In terms of financial implications, setting up a national system as described is anticipated to require an investment between £200,000 and £250,000 annually. This could extend to a per-breed basis, but with evolving initiatives like mixed breed genomics or strategies centred around dairy-derived beef, there exists potential to fine-tune these costs for optimal returns.

6c. Breeding for feed efficiency - sheep

- **Technology** - For large scale recording of feed intake for breeding programmes, automated feed intake recording equipment, suitable for recording individual animal intakes from groups of sheep in indoor pens, is closest to wide-scale implementation. Equipment designed for sheep is currently on the market (only a few international suppliers). This technology is being used in research breeding programmes in several countries. Recommended protocols include a training period (~2 weeks) for animals to acclimatise to the equipment and diet, followed by a recording period of ~6 weeks where regular live weights are measured and daily feed intake. Selection for feed efficiency has proven successful in research flocks, resulting in breeding stock selected for RFI becoming available in some countries and breeds. Could be used in conjunction with genotyping to provide genomic breeding values for feed efficiency. Protocols, SOPs etc. developed internationally and shared across countries. Research underway to test in UK sheep systems and breeding programmes (currently being measured in 1 commercial breeding programme) and fully understand genetic relationships with

[3] https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=18227

other important traits, including methane emissions, in order to develop genetic selection index including feed efficiency (and potentially methane emissions) with optimal weightings across traits.

- **User** – Some pull from commercial breeders and their customers (lamb producers, retailers, consumers). Measurements could be taken on farm but require a large shed and are time consuming (~8 weeks per batch of animals). Technician expertise required to monitor, clean, and analyse data. May be more feasible within a central progeny test structure. Some breeding companies and levy bodies engaged in initial UK research trials.
- **Market** - Market pull from retailers and consumers for low-methane red meat. Market for feed efficient breeding stock (selling from breeders to commercial lamb producers) may depend on demonstration of financial benefits and also links to incentives / subsidies / penalties attached to reduced methane emissions and the ability of assessment mechanisms (e.g., carbon calculators) to account for potential methane reductions within systems. The proportion of UK sheep that are performance recorded within formal breeding programmes is low, with between 0-30% of rams used having estimated breeding values (EBVs), depending on breed (Boon and Pollott, 2021; SheepBreedSurvey4295_130821_WEB.pdf (windows.net)). There is therefore substantial scope to expend this market by offering breeding stock with EBVs for hard to measure traits relating to methane emissions and feed efficiency. Cost per feed efficiency phenotype in the region of £300 per animal.
- **Societal** – Need to house and feed sheep indoors for recording of feed efficiency could damage the perception of natural, extensive, grass-fed sheep from UK systems. No major issues foreseen. General public generally recognise the importance of cost-effectiveness and reduction of waste in food production systems.
- **Regulatory** – No regulation required. Most feed intake recording equipment allows sheep to be housed in group pens under commercial stocking rates in line with welfare code recommendations.
- **ER /animal/d** - Typically, selective breeding can achieve annual rates of response of between 1% and 3% of the mean in the trait (or index) under selection. Contradictory evidence has been found for the effect of selective breeding for feed efficiency (residual feed intake, RFI) on methane emissions from sheep. Some studies suggest total emissions are reduced by ~6% from a 10% improvement in RFI in sheep (Hegarty et al., 2010 - https://doi.org/10.1071/AN10104; De Barbieri et al., 2020 - Book of Abstracts of the 71st Annual Meeting of the European Association for Animal Production (eaap.org)). On the other hand, other studies (Johnson et al.,2022 - https://doi.org/10.3389/fgene.2022.911639; Tortereau et al., 2023 - Improving feed efficiency in meat sheep increases CH4 emissions

measured indoor or at pasture (inrae.fr)) report unfavourable relationships between RFI and methane emissions – more efficient sheep producing more methane per day.

- **ER /kg lamb** – potentially similar to g/animal/d as maintaining genetic improvement in growth and carcass traits. De Barbieri et al. (2020) reported 8% lower emission intensity in high-efficiency Australian Merino lambs compared to low efficient counterparts.
- **Time to reach average RL 8** – would need change in breeding programme structure, potentially a central progeny test format where lambs from different farms are recorded with feed intake recording equipment. Phenotypes slow and expensive to collect, so several years to amass sufficient records for genomic breeding value derivation, depending on uptake. Records are being collected within 1 large commercial breeding programme alongside genotypes.
- **Co-benefits** - Increased production efficiency from breeding for feed efficiency, as well reduced inputs**.** Permanent and cumulative changes through breeding. Financial savings.
- **Costs** - Indoor housing and feeding required. Expensive phenotype per animal (current estimate ~£300 per lamb). Requires change to breeding programme structure, e.g., central progeny test.

6d. National genetic evaluations feed efficiency - dairy

- **Technology:** National dairy genetic evaluations use cutting-edge genomic technologies combined with traditional breeding techniques. They allow for the assessment of an animal's genetic potential for feed efficiency, meaning how well a cow can convert feed into milk. By utilising genomic data, breeders can make more informed selections, speeding up the breeding process and ensuring cows that consume less feed for every litre of milk they produce are chosen. Over time, this contributes to a more feed-efficient and environmentally friendly dairy herd. (TRL: 8)
- **User:** Dairy farmers, breeders, and dairy companies will be the primary users of this technology. These evaluations assist in making informed decisions regarding breeding, thereby ensuring the propagation of feed-efficient traits. (URL: 8)
- **Market**: As genetic improvement has high uptake given the level of artificial insemination in the dairy the core infrastructure is in place (MRL: 8)
- **Societal:** No major barriers as technology is already routinely deployed in the industry (SRL: 8)
- **Regulatory:** Regulatory bodies are supportive or accommodating of the use of genetic evaluations to promote feed efficiency in dairy cattle. A high score may indicate regulatory incentives or fewer barriers.

- **Annual mitigation of methane emissions (%):** 1% CH_4/yr, cumulative. This indicates a progressive reduction in methane emissions from dairy cows by improving feed efficiency through genetic evaluations.
- **Annual mitigation per unit of production (%):** 1.5-2% CH_4/kg milk solids/yr, cumulative. This metric means that for every kilogram of milk solids produced, there is a cumulative reduction in methane emissions due to improved genetics.
- **Time to reach average RL 8:** 1-2 generations (2-4 years). The genetic evaluations and subsequent breeding decisions will start showing significant results within 2 to 4 years.
- **Co-benefits:**
    1. Reduction in feed costs: By improving feed efficiency, farms can reduce the amount of feed required per cow, leading to cost savings.
    2. Optimising feed conversion on current/future diets: Improved genetics can ensure cows convert feed optimally irrespective of changes in feed types or quality.
    3. Potential crossover benefit for dairy-beef if integrated: Genetic improvements in dairy cattle can potentially be transferred to beef cattle if breeding programs are integrated, enhancing feed efficiency in both sectors.
- **Costs:** Using genomics for feed efficiency evaluations requires an upfront investment in research and data collection. The costs are roughly similar to those of beef breeds (£150k-£200k/yr), mainly to gather population-relevant feed intake and production records. The dairy sector may have a head-start due to better infrastructure and collaboration with industry recording. There are potential savings and cost-sharing opportunities, especially if dairy and beef efficiency evaluations are integrated.

6e. Breeding for feed efficiency (within commercial breeding companies) - dairy

Similar to 6d – however routes for cost saving and relating co-benefits at a wider population level are more limited given private company.

7a. Breeding for methane mitigation using respiration chamber measurements – beef

- **Technology –** The 'gold standard' technique for measuring methane emissions is respiration chambers. Recently, Martinez-Alvaro et al. (2022) predicted, based on data from beef cattle measured for methane emissions using respiration chambers, a heritability of 0.33, which is of a similar magnitude as for growth rate and feed conversion efficiency. This is a further indication that methane emissions are controlled by animal genetics/genomics. The challenge is that measurement of methane in respiration chambers is too costly for large scale breeding, but of high value for research. Validation trials are currently ongoing (InnovateUK-funded project). Alternative methodologies for measurement of methane in practical farm conditions are available (e.g., GreenFeed system). These systems need validation for usefulness within large-scale breeding.

- **User -** Breeding organisations have currently limited uptake of GreenFeeds due to the high cost and lack of incentive for breeding low methane-emitting cattle.
- **Market -** The market for accurate selection for methane emissions is limited due to the high measurement cost.
- **Societal –** Mitigation of methane emissions is seen as controversial among marginal interest groups, e.g., rare breeds will probably not have the population size and logistics to achieve sufficient recording of methane emissions from beef cattle for genetic/genomic selection.
- **Regulatory -** approval of breeding for methane emissions is highly likely.
- **Annual mitigation of methane emissions (%) -** Depending on the intensity of selection and the generation interval (could be as short as 2.5 years using genomic selection), the following reduction in methane emissions have been estimated in growing finishing beef cattle using methane emissions measured in respiration chambers (Martínez-Álvaro et al., 2022a):
    - Selection of 1% of the best animals, annual reduction of 5%.
    - Selection of 30% of the best animals, annual reduction of 2%.
    - This annual response is permanent and is cumulative. Animal breeding has been shown to be highly cost-effective for similarly heritable traits (e.g., growth rate).
- **Time to reach average RL 8 -** The time to implement accurate selection for reduced methane emissions, based on large scale recording of methane emissions, depends most likely on incentives given to farmers using AI and the use of semen of bulls with breeding values for low methane emissions. This would attract breeding organisations to implement a selection strategy such as microbiome-driven breeding for mitigation of methane emissions in cattle.
- **Co-benefits –** There are no consistent co-benefits reported.
- **Costs -** The high cost associated with recording methane emissions and the low level of artificial inseminations (AI) is hampering the implementation of selection for methane mitigation in beef cattle.

7b. Breeding for reduced methane emissions – sheep

- **Technology** – Portable Accumulation Chambers (PAC) most suitable for wide-scale application and ready for market. Being used in breeding programmes in NZ, Ireland, and wide-scale research trials elsewhere (Australia, Norway, Uruguay). Can measure ~60-80 sheep per day using 1 trailer with 12 chambers - representative sample of sheep within a breeding programme can be measured to provide breeding values for methane emissions. Two units (of 12 trailers) currently in UK – being used for research. Could be used in conjunction with genotyping to provide genomic breeding values for methane emissions. Business models, protocols, SOPs etc. developed internationally and shared across countries. Only 1 current manufacturer for limited sales (AgResearch NZ). Research underway to test in UK sheep systems and breeding programmes and fully understand genetic relationships with other important traits in order to develop genetic selection index including methane emissions with optimal weightings across traits.

- **User** – Some pull from commercial breeders and their customers (lamb producers, retailers, consumers). Measurements taken on farm (portable trailer of PACs can move between farms) and require feeding and management protocols to be followed in advance by breeders. Not too large a step for breeders already performance recording and measuring a number of phenotypes on farm. Some breeding companies and levy bodies engaged in initial UK research trials to fine tune protocols and models for UK breeding programmes. UK technicians already trained in measurement protocols and taking research measurements.
- **Market** - Market pull from retailers and consumers for low-methane red meat. Bred directly for low methane emissions - easy to understand and market. Market for low methane breeding stock (selling from breeders to commercial lamb producers) may depend on incentives / subsidies / penalties attached to methane emissions and the ability of assessment mechanisms (e.g., carbon calculators) to account for potential methane reductions at the individual animal level within systems. The proportion of UK sheep that are performance recorded within formal breeding programmes is low, with between 0-30% of rams used having estimated breeding values (EBVs), depending on breed (Boon and Pollott, 2021). There is therefore substantial scope to expend this market by offering breeding stock with EBVs for hard to measure traits relating to methane emissions and feed efficiency. Cost per PAC phenotype in the range £40-100 per animal. NZ protocols suggest 120 lambs measured per farm in performance-recorded flocks.
- **Societal** – Small risk of consumer concerns for animal welfare due to the requirement for sheep to be handled and isolated in chambers for ~50 mins during measurement. Can be justified by initial research and protocols in place to optimise welfare. Potential environmental impact from towing chambers around the country to take measurements may raise societal concerns. Some livestock farmers and stakeholders feel the technology is unwanted / inappropriate, as they argue that livestock are not the cause of global warming. Otherwise, positive societal feedback from initial use of these technologies in the UK.
- **Regulatory** – currently PAC measurements require to be performed under home office licence in the UK (unproven procedure in UK systems). It is anticipated that

this will not be the case after initial research projects are complete (~3 years) and these measurements can be taken in breeding programmes as standard management procedures. Procedure is non-invasive and no sedative / other drugs are required.

- **ER /animal/d** - The commercial and physical impact of a national breeding scheme in NZ to lower methane emissions was estimated as 0.58%/year using genomic selection. After 20 years, annual methane production in 2040 was predicted to have reduced by 7.5% per annum saving a total of 4490 kt of CO2e over the 20-year period with a cumulative saving of CO2e assuming GWP100 (Rowe et al., 2021 - 5Rowe24015.pdf (aaabg.org)). They demonstrated a 1-2% reduction per annum in commercial research flock since methane breeding values were included in the index, whilst maintaining genetic gain for all other traits. They estimated that they would achieve less than one half of this reduction in the breeding tier in the national flock, given likely adoption rates, and including genetic lags in the deployment of improved livestock. These benefits would be achievable by the development of low-cost high throughput phenotyping for methane combined with the widespread adoption of genomic selection.
- **ER /kg lamb** – potentially similar to g/animal/d as maintaining genetic improvement in growth and carcass traits.
- **Time to reach average RL 8** – adoption into at least one industry breeding programme expected after 3-year research project which is now underway.
- **Co-Benefits –** These genetic gains can be achieved whist maintaining genetic progress in maternal and production traits. Permanent and cumulative changes due to breeding. Targets grass-based systems, as typical for UK sheep.
- **Cost -** Requires expensive equipment and transport of equipment around the country. Cost per PAC phenotype in the range £40-100 per animal.

7c. Breeding for reduced methane emissions – dairy

- **Technology:** Breeding for reduced methane emission involves genetic and genomic tools to identify dairy cattle that emit less methane. Direct measurements can be taken using chambers, though field deployable kits, such as GreenFeeds, offer more cost-effective solutions for larger-scale measurements. Genomic selection tools can be employed to predict the breeding value of an animal for reduced methane emissions. (de Haas et al., 2011).
- **User:** Dairy cattle breeders, farmers, and dairy production enterprises aiming to reduce the environmental footprint of their operations are the primary users of this technology.
- **Market:** With increasing consumer awareness of the environmental impact of their food choices, there is a growing demand for sustainably produced livestock

products. Consumers are becoming more aware of the environmental impact of their food choices, and some are willing to pay a premium for products produced in a sustainable manner (Clark & Tilman, 2017)

- **Societal:** Breeding for reduced methane emissions contributes to global climate change mitigation efforts, given methane's potency as a greenhouse gas.
- **Regulatory:** Governments and international bodies might provide guidelines or even incentives for breeding programs that aim at reducing greenhouse gas emissions from livestock farming (Gerber et al., 2013)
- **Annual mitigation of methane emissions (%):** Using breeding strategies, methane emissions can be reduced by 0.5%-1% CH_4 per year, cumulative. This is in addition to savings achieved from feed efficiency.
- **Annual mitigation per unit of production (%):** The mitigation translates to a 1-1.5% CH_4 reduction per kilogram of milk solids per year, cumulative.
- **Time to reach average RL 8:** Achieving the desired reduction levels in methane emissions is estimated to take 1-2 generations, which corresponds to 2-4 years.
- **Co-benefits:** A high correlation exists between methane emissions and feed efficiency. Therefore, selecting for reduced methane emissions can potentially offer correlated savings in feed efficiency. This is especially significant if feed efficiency is not already part of the breeding goal, though it's worth noting that feed efficiency is incorporated in the UK's breeding goal.
- **Costs:** The initial investment in methane measurement is substantial. Establishing a relevant dataset using chambers can be expensive. However, the use of field deployable kits like GreenFeeds makes it more affordable. Still, an estimated upfront cost of £500k over the first 3-5 years is anticipated for dataset establishment, with an ongoing annual cost of £250k to maintain the dataset.

8a&c. Microbiome-driven breeding to reduce methane emissions – beef and dairy

- **Technology –** The rumen microbiome comprises of bacteria, protozoa and fungi which can convert, by fermentation, fibrous feed (such as grass) into nutrients (volatile fatty acids, microbial protein), which are the main energy and protein sources for ruminants to produce meat and milk. However, when this fermentation is inefficient, an excess of hydrogen is produced which is used by methanogenic archaea to produce methane which is expelled through the mouth and nose into the atmosphere. Microbiome-driven breeding is focussed on selecting animals with a rumen microbiome composition that is more efficient at fermenting feed, resulting in less excess hydrogen and subsequently less methane. This methodology is therefore focussed on the underlying cause of methane production. The methodology has recently been developed (published in

Martínez-Álvaro et al. 2022). The core-microbiome has been shown to be stable, therefore only one rumen sample is necessary to characterise the composition of the rumen microbiome. This microbial composition has been shown to be influenced by animal genetics. The most efficient way to implement microbiome-driven breeding is to sequence the microbial DNA of rumen samples and the animal DNA for genomic selection and then select those animals with a microbiome composition that results in the lowest methane emissions. The microbiome-driven breeding strategy is substantially more cost-effective than a genetic evaluation that requires costly direct measurements of methane emissions from individual animals. In addition, AI would provide a population structure which would make the selection criteria of animals (i.e., genomically estimated breeding values of methane emissions based on microbiome information) substantially more accurate and dissemination over the entire animal population much faster than using natural service.

- The use of microbiome-driven breeding has been developed in a beef breeding environment together with the international breeding company Genus plc. In an ongoing Innovate UK project with Genus plc., microbiome-driven breeding is being tested and validated, and the functionality is being optimised on different beef populations. There are substantial differences between dairy and beef cattle in the microbiota composition, therefore, microbiome-driven breeding to reduce methane emissions in dairy must be tested on these breeds before further recommendation for its use.
- **User –** Microbiome-driven breeding combined with genomic selection (i.e., selection based on many DNA Markers of the host animal) needs the structure, logistics, bioinformatic knowledge, testing facilities, etc. of an animal breeding organisation to obtain the estimated breeding values for methane mitigation, based on the sampling of rumen content and DNA of the animals within a genetic analysis. The farming community could then buy semen from bulls with breeding values for low methane emissions from these breeding organisations. For an advanced breeding organisation, relatively small organisational changes are needed to use microbiome-driven breeding. The methodology can be combined with lower-cost technologies to measure methane emissions (e.g., GreenFeed technology).
- **Market –** The market for microbiome-driven breeding is expected to increase due to the increasing need to mitigate methane emissions. To facilitate adoption, within the farming community, incentives are required because of the cost involved in including the new trait (methane emissions) within a wider breeding programme. Microbiome-driven breeding has been launched in limited scope in one breeding company in beef cattle. For dairy breeding, a business model can be described for this breeding strategy.

- **Societal –** Microbiome-driven breeding is seen as controversial among marginal interest groups, e.g., rare breeds will probably not have the population size and logistics to achieve sufficient reduction in methane emissions using this methodology. However, if its effectiveness can be demonstrated in further research using across breed evaluations, some progress could also be achieved in rare breeds. Methods of rumen sampling may also be controversial for the general public / consumers for animal welfare reasons.
- **Regulatory –** Currently rumen sampling using a stomach tube must be performed under home office licence in the UK, if performed for research purposes only. The sampling of rumen contents using a stomach tube is considered to cause a low level of distress to the animal, taking ~5 minutes. This technique could be integrated as common practice within a breeding organisation allowing selection of breeding animals based on their natural variation in microbiome profiles and methane emissions. Therefore, the application of the methodology is considered likely to be approved as a non-regulated procedure.
- **Annual mitigation of methane emissions (%) –** Depending on the intensity of selection and the generation interval (could be as short as 2.5 years using genomic selection), the following reduction in methane emissions have been estimated in growing finishing beef cattle (Martínez-Álvaro et al., 2022a).
    - Selection of 1% of the best animals, annual reduction of 7%.
    - Selection of 30% of the best animals, annual reduction of 3%.
    - This annual response is permanent and cumulative. With continued selection of the top 1% of animals for breeding, it is expected to result in a cumulative reduction in methane emissions of ~50% in 10 years' time. Animal breeding has been shown to be highly cost-effective for similarly heritable traits such as growth rate. Roehe et al. (2016) also demonstrated that the reduction of methane using microbiome information is independent to the diet.
- **Time to reach average RL8** – Estimated at 4 years for microbiome-driven breeding, due to advanced research in beef cattle. Dairy needs research to develop the genetic prediction of methane emissions based on the rumen microbial community, so time to reach RL8 could be longer in that sector. However, the dairy sector will benefit from the fact that microbiome-driven breeding in beef is in its validation phase, which can inform dairy research.
- **Co-benefits –** Microbiome-driven breeding can also be used for improvement of feed conversion efficiency, enhancement of meat quality (due to increased Omega-3 fatty acids in meat; Martínez-Álvaro et al., 2022b), and even to increase the accuracy of breeding values for recorded growth traits and consequently increase its genetic improvement. Additionally, microbiome-driven breeding can select animals for improved health, examples include the identification of animals

genetically prone to acidosis and other dysbiosis of the rumen ecosystem, or the use of microbial profiles as biomarkers for other pathogenic disease, e.g. caused by the nematode Ostertagia ostertagi.

- **Costs -** The main cost for implementation of microbiome-driven breeding is associated with rumen sampling, sample storage, microbial DNA sequencing, animal genotyping, genetic evaluation, testing of progeny of bulls, selection of bulls, storage and dissemination of semen. The cost of implementation can be largely reduced in a running breeding programme where e.g., animal genotyping, genetic evaluation, testing of progeny of bulls, selection of bulls, storage and dissemination of semen are routinely carried out. A low-cost sequencing technology has been developed to determine the microbiome composition. The cost to the user (farmer) would include the cost of semen which is currently around £10/straw for beef semen, £20/straw for conventional dairy semen and £30/straw for sexed semen (Scotland's Farm Advisory Service, 2022). We assume that the cost for semen using microbiome-driven breeding for methane mitigation may increase by 10%- 30%.

8b. Breeding for microbiome changes - sheep

- **Technology** - Methane emissions can be predicted by microbiota communities sampled from rumens of sheep, using a tube inserted down the throat into the rumen through which a sample of rumen fluid can be collected using a syringe. The microbial community is controlled by the host itself, as well as by the feed, and so it is possible to select hosts that favour a microbial fermentation with lowered methane emissions. Most methods for obtaining microbial DNA and subsequent sequencing of an animal's microbiome are too expensive to implement in commercial selection programs. Researchers in New Zealand have developed and tested a methodology that offers fast, low-cost, high throughput profiling of rumen microbiomes using Genotyping-by-sequencing (GBS). Results show that microbial profiles are heritable and correlated with methane emissions and feed intake (Rowe *et al.*, 2019). The relationships between microbial profiles and methane emissions in sheep are not yet validated for UK sheep populations, but this is planned in the next 3 years within a InnovateUK research project.
- **Users** – basic equipment is required (gag, syringe, and tube with weighted device on the end to maximise sample quality), but a skilled operator to extract the rumen sample (currently under HO licence), which is an invasive procedure. The sample would have to be processed and shipped for analysis following specific protocols. An experienced lab would be required to extract and profile the microbial DNA. This will then need to be related to the profiles determined by research groups (e.g., AgResearch in NZ) as being indicative of higher or lower methane emissions.

It is not yet clear how these data could be integrated into UK sheep breeding programmes.

- **Market** - Market pull from retailers and consumers for low-methane red meat. Market for low methane breeding stock (selling from breeders to commercial lamb producers) may depend on incentives / subsidies / penalties attached to methane emissions and the ability of assessment mechanisms (e.g., carbon calculators) to account for potential methane reductions at the individual animal level within systems. The proportion of UK sheep that are performance recorded within formal breeding programmes is low, with between 0-30% of rams used having estimated breeding values (EBVs), depending on breed (Boon and Pollott, 2021). There is therefore substantial scope to expend this market by offering breeding stock with EBVs for hard to measure traits relating to methane emissions and feed efficiency. Lab costs per phenotype estimated in the range £40-60 per animal.
- **Societal** – Consumer may have concerns due to mild invasive nature of the rumen sampling.
- **Regulatory** – currently rumen sampling must be performed under home office licence in the UK, for research purposes only. This may change if it became a standard management procedure used to make management (breeding) decisions, however due to the invasive nature of the procedure, it may then have to be performed by a vet. This is unknown at this stage. Potential requirement to send biological samples abroad to analyse.
- **ER /animal/d or ER/kg lamb** - Typically, selective breeding can achieve annual rates of response of between 1% and 3% of the mean in the trait (or index) under selection. Information seems to not yet be available on how selection on rumen microbial profile of sheep can reduce methane emissions in terms of % per year / generation.
- **Time to reach average RL 8** – further UK research required to determine relationships between microbiome and methane emissions from sheep. Logistics of sample collection and analysis would require substantial planning, training, and infrastructure. Process for incorporation into breeding programme not yet clear.
- **Co-benefits** – Potential co-benefits in feed efficiency, animal health, meat quality, etc.
- **Costs -** Implementation cost and running cost. Lab costs per phenotype estimated in the range £40-60 per animal. Also costs of associated research required prior to UK implementation for sheep.

9a. Sexed semen – sheep

- **Technology:** Sexed semen technology separates sperm cells based on their X or Y chromosome content, allowing for offspring sex selection. For sheep, prioritising female offspring can emphasize wool and meat production over rams that might not be used for breeding.

- **User:** Sheep farmers, breeders, and AI technicians and providers. However, with the complexities of sheep reproduction the feasibility of AI on a large commercial scale is low.
- **Market:** See user comments, low market readiness or potential.
- **Societal:** Reducing overall sheep numbers by focusing on ewes can cut methane emissions, with potential societal approval given environmental benefits and farming optimisation (Cottle, D.J., 2013).
- **Regulatory:** Regulations may ensure safe and ethical technology use, addressing animal welfare and potential long-term effects (FAO, 2019).
- **Annual mitigation of methane emissions (%):** Mitigation depends on adoption scale and regional practices, but a significant sheep population reduction can have notable impact.
- Annual mitigation per unit of production (%): Mitigation per unit might arise from fewer animals with similar or higher production levels.
- **Time to reach average RL 8:** Reaching RL 8 would take years, considering factors like research and market acceptance.
- **Co-benefits:**
    - Improved flock management and productivity.
    - Improved breeding and reproductive function.
    - Economic benefits from reduced maintenance costs.
- **Costs:**
    - Initial tech investment.
    - Higher AI costs.
    - Management costs.

9b & c. Sexed semen – beef and dairy

- **Technology** (Beef: 7, Dairy: 9): Sexed semen technology, used in both beef and dairy industries, sorts sperm based on their X or Y chromosome content, allowing the selection of the sex of the offspring (Seidel, G.E., 2007).
- **User** (Beef: 6, Dairy: 7): For both beef and dairy, the primary users are farmers, breeders, and AI technicians/providers (Lucy, M.C., 2019).
- **Market** (Beef: 6, Dairy: 8): The market encompasses producers (both beef and dairy) aiming to optimize herd composition and reduce GHG emissions, backed by firms in animal reproduction technologies (Frijters, A.C.J., 2000).
- **Societal** (Beef: 8, Dairy: 8): The societal impact for both beef and dairy is tied to the potential for reduced GHG emissions. Beef benefits from the faster growth

rates of male cattle, while dairy can reduce surplus male calves that have a lower productive value (Cottle, D.J., 2013).

- **Regulatory** (Beef: 8, Dairy: 8): Both industries would be governed by regulations ensuring the safe and ethical use of the technology, with considerations for animal welfare and long-term environmental effects (FAO, 2019). As already readily available in dairy and beef, albeit in lower volume, the technology has little deployment barriers.
- **Annual Mitigation of GHG** (Beef: 10-20%, Dairy: 20-25%): Beef sees a varied mitigation percentage based on production methods (suckler vs. finishing beef), while dairy boasts a significant potential reduction, particularly when considering surplus male calves (Wiedemann, S.G., 2015).
- **Annual Mitigation per Unit of Production** (Beef: 10%/kg meat, Dairy: 10%/kg milk): Both industries stand to see a per-unit reduction in GHG emissions due to optimised herd composition and reduced wastage.
- **Time to Reach Average RL8** (Beef: 5 yrs, Dairy: 0 yrs): Beef lags due to its traditionally lower AI rates, signalling the need for more significant AI adoption, while the dairy industry has already widely deployed this technology (Mota, R.R., 2020).
- **Co-benefits:** Beef cattle, due to their faster growth, can lead to quicker turnovers. Dairy cows, through the reduction of surplus male calves, and targeted use of both sexed dairy and beef semen, may see larger benefits if the suckler herd were reduced (King, W.A., 2010; Holden & Butler 2018).
- **Costs:** For beef, challenges include low AI rates and the higher costs of sexed semen. Breeding companies would also need to sex beef bulls. The dairy industry faces the direct costs of sexed semen. However, broader societal benefits from changing the herd structure in dairy may require external support (FAO, 2019).

10a-c. CH_4 direct air capture – GreenSheds

- **Technology –** A consortium of technology partners and academics (led by SRUC) have won funding to build and demonstrate an integrated low-carbon, circular, cattle and vertical farming system, which captures methane (CH_4) from housed cattle and utilises the outputs (heat, power, carbon dioxide (CO_2)) to yield low-carbon produce (meat, vegetables/fruits) and optimise resource efficiency. The system combines five core proven technologies to create the "GreenShed System": (i) High-volume air recirculation/conditioning/sterilisation system, aligned with a novel engineered solution to capture CH_4 from cattle sheds, (ii) Micro-anaerobic digester (AD) with built in feedstock pre-treatment to improve efficiency. This produces biogas from manure and waste feed, (iii) Novel ultra-lean combined heat and power (CHP) engine, (iv) A Wastewater Treatment System

(WWTS) to remove and clean the water from the digestate, reducing the storage requirements and providing re-usable water, and (v) Vertical farming to utilise low-cost, low-carbon AD/nitrogen fixing outputs and return oxygen-rich air to the shed. Feasibility funding from the Scottish Government and Phase 1 of the BEIS Direct Air Capture/Greenhouse Gas Removal (DAC/GGR) programme has developed the GreenShed design (using SRUC's GreenCow respiration chamber facility to test/prove the concept). With further funding from Phase 2 of the BEIS Direct Air Capture/Greenhouse Gas Removal programme the consortium is currently:

  - building the prototype GreenShed
  - pilot testing methane capture and conversion combined with vertical farming and nutrient production.
  - conducting animal welfare assessments of cattle within GreenShed
  - developing a "digital twin" of GreenShed and validating using prototype data.
  - Conducting full Life-Cycle-Analysis (LCA) (i.e., heat, nutrients, power, carbon savings).
  - finalising the business model: pricing and ROI strategy, tested with farmers and processors/retailers.
  - creating case studies covering various legacy infrastructure and production systems.

- **User –** Users (farmers, supply chain) are aware of the need for technological solutions to reduce GHG emissions. Direct engagement with farmers (in Phase 1 of GGR/DAC) through semi-structured interviews identified that: respondents recognised the need for technology to address the GHG impact of beef production, and the potential for GreenShed to provide a solution for sustainable beef. The key opportunity identified for GreenShed was for specialist beef finishing units, where cattle are housed and fed intensively for the final stage of the production cycle. Two areas emerged which warrant further research, (being conducted in Phase 2): consumer perceptions of the system and return on investment for farmers.
  - **Market –**A conservative target market for this technology has been identified as 3% initial market penetration of the specialist (100+ head) UK beef finishing farms, equating to 180 sheds; and 0.5% of EU specialist beef finishing farms, equating to 320 sheds; totalling 500 sheds by 2030. At 222tCO_2eq/annum removed per shed, this will achieve 111kt CO_2eq/annum removal by 2030. Post project (project end date – 31st March 2025) will focus on GreenShed commercialisation and roll-out (anticipated within 3-5 years): Joint Venture formation - UK roll-out - Pilot producer scheme - EU sales launch.

- **Societal –** The GreenShed consortium have been delivering stakeholder research (with consumers and 2 retail supply chains) to explore the perception of the GreenShed concept, understand the willingness-to-pay for low-carbon produce, and understand barriers to adoption (using qualitative and quantitative social science techniques). Key outcomes to date: consumers are generally interested in the concept, and to find solutions for carbon reduction (to reduce the guilt associated with consuming red meat), but animal welfare concerns over-ride concerns associated with carbon emissions. Therefore, any new solution will need to adhere to current welfare standards. Consumers with concerns around carbon emissions are prepared to pay a premium for low-carbon produce – but this needs to be quantified (currently being addressed using quantitative social science). In addition, housing animals within a shed generates negative consumer perceptions of beef production. Although GreenShed is proposed as a retrofit onto existing buildings, integrating with current production systems, and offering improved environmental conditions - animal welfare concerns need to be carefully considered/addressed.
- **Regulatory –** Currently the use of GreenShed is required to be performed under home office licence in the UK (unproven procedure in UK systems). It is anticipated that this will not be the case after the currently funded research project (BEIS, DAC/GGR, GreenShed Phase 2) is complete (March 2025). The research project is assessing technical performance, carbon reduction potential alongside animal welfare. Commercial installations following project completion are not expected to require home office licencing.
- **Emissions Reduction –** historical and new pilot data (>10 years of data from a range of animal sizes/types) from SRUC's GreenCow facility (respiration chambers – gold standard technique for methane measurement) has been used in Phase 1 work to model the expected reduction in CO_2eq from the GreenShed concept (currently estimated at 222tCO_2eq/annum for each GreenShed designed to house 100 animals – all year round). The first GreenShed has been built on SRUC premises (near Edinburgh, UK). Data collection is underway to monitor, report and verify the technical performance of GreenShed, and its carbon removal potential.
- **Time to reach average RL 8** – 5-10 years.
- **Co-benefits –** Improved environmental conditions (environmental control) has the potential to improve production levels and animal welfare. Increased production outputs (beef sales premium, new horticulture output).
- **Costs –** Costs being refined during GreenShed demonstration (throughout 2024-2025). Initial costs ~400k, with a ROI of 7-8 years.
- For further detail please refer to the final published report from Phase 1 of the BEIS DAC/GGR programme:

- https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1075309/sac-commercial-greenshed-phase-1.pdf

11a-c. CH_4 direct air capture – halters

- **Technology –** ZELP is a wearable technology designed for cattle. The device fits to the animal's head with a "mask" sitting above the nostrils. The mask contains methane oxidising technology, converting CH_4 to CO_2, which has a lower global warming potential (non-fossil fuel sources of CH_4 have a GWP of 80.8 over 20 years), as it is eructed from the animal. The device also contains 'sensors' (which are not defined) collecting data (activity, temperature, and rumination) which ZELP claims can detect heat, indicate animal production efficiency and welfare using machine learning algorithms. The device can be used after weaning from 6-8 months and for the duration of the animal's life.
- **User –** Currently there is insufficient available evidence to encourage uptake of this technology. Concerns around the welfare impacts of wearing the device also need to be addressed. If evidence emerges supporting the efficacy of this technology (without impacting on behaviour and welfare) this could be used on any animal generating methane - grazed or housed.
- **Market -** The devices are available on a subscription-based model. They can be funded by corporations or farmers, with the funder receiving the generated carbon credits which can be sold or used for internal emissions off-setting. ZELP are currently developing VERRA and Gold Standard methodologies for carbon credit verification and hope to have these in place by mid-2023 (ZELP, pers. comm.). In return, farmers receive the activity, production efficiency and methane emission data generated by the device. ZELP claim the devices can be used continuously for up to four years with little to no maintenance requirements.
- **Societal -** There may be negative implications (shared with neck-borne wearable devices) for feeding and social behaviours.
- **Regulatory –** We are not aware of direct regulation of 'wearable devices' (a category that also includes various neck-mounted and leg-mounted sensors such as accelerometers). The Code of Practice for the Welfare of Cattle states "If you are marking the cattle with neck bands or chains, and tail bands or leg bands (which you use for herd management identification purposes) you should fit them carefully and adjust them as necessary to avoid causing the animals any unnecessary pain, suffering or injury. ZELP technology is not within the scope of a recent report from the Animal Welfare Committee on the welfare implications of virtual fencing systems (another 'wearable' technology).

- **Emissions Reduction –** No claims about the efficacy of enteric methane oxidation are made on the ZELP website (accessed 29th August 2022). A press release dated July 2021 is reported to state: 'the technology has already demonstrated a 53% reduction in methane emissions' (Cargill and ZELP align to tackle methane emissions in the dairy industry (feednavigator.com)). As of November 2024, there were no peer reviewed publications verifying the efficacy of ZELP as a method for oxidising enteric methane emissions at the point of emission. The ZELP website states multiple *in vivo* trials have been undertaken but no citations or reports of results are provided. No peer reviewed journal papers have been published. However, ZELP received EU funding through Horizon2020 and a report on the project on the funder website state "The preliminary tests show an average 26.5 % reduction in methane emissions by animals wearing the device, with a maximum reduction achieved of 32 %". It is not defined whether reductions are per day, or per unit of product. Not clear what type of cattle these data refer to (beef or dairy).
- **Time to reach average RL 8 –** estimated at >10 years.
- **Co-benefits –** potential positive implications associated with increased and automated monitoring of individual animals. From the ZELP website: 'We track activity, temperature, rumination and feed to identify potential signals of disease…'.
- **Costs –** unknown.
- Detail captured in report for Tesco-WWF in 2022/2023 (not yet published).

12a-c. Forage adjustment – grass genetic improvement - high sugar varieties

- **Technology**. Varieties of perennial ryegrass with elevated concentration of water-soluble carbohydrate (WSC, = 'sugar') have been developed over 30 years, primarily with the aim of improving capture of nitrogen and microbial protein production during digestion.
- **User**. No barriers to the use of high sugar grass (versus other varieties) by farmers.
- **Market.** No barriers.
- Societal. General acceptance of varieties (conventionally bred) with a promised environmental benefit.
- **Regulatory**. No barriers. All new grass varieties follow the same, well-established testing and evaluation processes to become established on national lists of recommended varieties.
- **Emissions reduction**. Low and high WSC varieties have been compared in several *in vivo* experiments. As in all nutritional studies, a change in the dietary concentration of one nutrient must mean changes in others. The effect of higher WSC on methane may therefore depend on what that WSC has displaced. Where WSC dilutes plant cell walls, productivity may be improved, and methane intensity reduced. However, where WSC dilutes protein (which has lower methanogenic

potential than carbohydrate), methane emissions may be little affected. Jonker et al. (2016) compared high and low WSC varieties in sheep, harvesting at different times of the year across two years. While both methane production and yield were slightly lower (-8%) for the high WSC variety, grass WSC concentration was a poor predictor of methane production and yield. Staerfl et al. (2012) found no difference in methane emissions in cows offered dried grass (as the sole feed) made from either low or high sugar PRG. However, higher sugar in the grass was largely at the expense of lower crude protein. Although the higher sugars may have increased propionic acid production (not measured), the effect of this on methane may have been compensated by the lower methane production expected from the higher protein content of the low WSC grass. The lack of clear-cut relationships between WSC concentration and methane production or yield in *in vivo* experiments is consistent with Hammond et al. (2009), who interrogated a database of methane emissions from over 3,000 individual animals (sheep and cattle) and found only weak relationships between emissions and the composition of PRG.

- Mitigation of methane production (g/d): insufficient data (*in vivo*)
- Mitigation of methane intensity (g/kg milk or meat): insufficient data (*in vivo*)
- **Time to reach average RL8.** High-sugar varieties already have significant market share, but data to promote them as a tool for methane mitigation is not available. At least two years of coordinated experiments would be required, under Scottish conditions, to quantify methane benefits (if any).
- **Co-benefits.** Improved efficiency of N utilisation in the rumen (may improve productivity and reduce N excretion).
- **Costs.** Negligible cost difference between 'high sugar' and conventional varieties of perennial ryegrass.

13a-c. Forage adjustment – grass genetic improvement - high lipid grass

- **Technology**. Genetic engineering techniques are being used in New Zealand to increase the energy value of perennial ryegrass by increasing leaf lipid content. Grass growth trials are being conducted in the USA.
- **User**. It is unlikely that, if brought to market, high lipid grass would present any novel challenges to users.
- **Market, Societal, Regulatory**: as a product of 'genetic engineering', high lipid grass faces significant market, societal and regulatory barriers.
- **Emission reduction**. One *in vitro* rumen fermentation study has been reported (Winichayakul et al., 2020). Compared with a conventional perennial ryegrass, high lipid grass reduced methane production by 37% (fermentation was suppressed) and methane as a proportion of gas by 12%. Early promise.
- **Time to reach average RL 8.** 10-15 years.

- **Co-benefits.** Higher energy content likely to improve productivity.
- **Costs.** Not known.

14a-c. Forage adjustment – maize and whole crop cereal silages

- **Technology**. Maize and whole crop cereal silages do not suit every farm or farming system, but the UK has decades of experience in their growing and use, primarily as partial substitutes for grass silage.
- **User.** The elasticity of the acreage used for maize and whole crop cereals is not known. Farmers growing these crops, or who have grown them in the past, likely have some potential to grow more.
- **Market**. Milk and meat from animals fed these crops is not differentiated by most of the farmer's potential customers.
- **Societal**. There may be low level general concern about the use of small grain cereals for silage rather than to provide grain for human use, and the environmental consequences of maize (plastic is highly visible in the countryside, as are episodes of run-off from maize fields).
- **Regulatory**. No specific restrictions for these crops.
- **Emissions Reductions**. Compared with grass silage-based diets, maize and whole crop cereal silages are expected to increase dry matter intake, thus increasing methane production (g/d), and decrease methane yield (g/kg DMI) and methane intensity (g/kg milk or meat). Data from six treatment comparisons in four dairy cow experiments, where maize silage displaced grass silage, show no effect on methane production, -8% methane yield, and -5 % methane intensity. However, responses are variable, depending on the quality of the grass silage displaced, with improvements more apparent when dietary starch concentration is high. Whole crop wheat silage (WCWS) was compared with grass silage and maize silage by Gunal et al. (2018). For the diet based on WCWS, methane production was intermediate, and methane yield and intensity slightly lower than with diets based on grass or maize silage. At a systems level, O'Neill et al. (2011) compared cows grazing high quality perennial ryegrass with cows fed a total mixed ration (TMR) based on a relatively poor-quality maize silage. Cows fed the TMR produced more methane (+58%), with higher methane yield (+12%) and methane intensity (+15%). However, grazing cows consumed significantly more protein, which has a lower methanogenic potential than carbohydrates, and relied on body fat mobilisation to support milk production (not sustainable in the long term). Whole lactation studies are needed before general conclusions can be drawn about methane emissions from different farming systems based on different forages.
- **Mitigation of methane production (g/d):** no effect versus grass silage (based on *in vivo* experiments, dairy)

- **Mitigation of methane intensity (g/kg milk or meat):** maize silage -5% versus grass silage (crude mean, *in vivo*, dairy)
- **Time to reach average RL8:** At RL8 (opportunity to generate additional data and improve prediction of methane responses).
- **Co-benefits.** Productivity, improved Nitrogen Use Efficiency (milk or meat N / N intake)
- **Costs.** Already a commercial proposition for many farmers, based on productivity benefits. No additional costs to use for methane mitigation benefit.

15a-c. Forage adjustment – clovers and lucerne (alfalfa)

- **Technology**. White clover is primarily used in grazed pastures, with inclusion at around 30% of DM considered optimal for the performance of grazing animals. Red clover is primarily used as silage. Growth of lucerne is marginal in most of Scotland. These three legumes generally contain low concentrations of tannins and other phytochemicals suggested to exert direct effects on methane. However, combined with grass, they may reduce methane indirectly by increasing rate of digesta passage from the rumen.
- **User**. User concerns include establishment and persistency of these species in swards, weed control (e.g., docks in red clover) and risk of adverse animal health effects (e.g., bloat).
- **Market, Societal.** general positive perception of other benefits of forage legumes (e.g., biodiversity, nitrogen fixation leading to reduced use of high carbon footprint inorganic fertiliser).
- **Regulatory.** no specific barriers.
- **Emissions reduction**. Compared with perennial ryegrass *in vitro*, both white clover and red clover generated less methane, due to lower digestibility (Loza et al., 2021). However, methane as a proportion of total gas was increased. Effects of forage legumes on rates of passage – a mechanism likely to influence methane – cannot be simulated *in vitro*. *In vivo* data for effects on methane are inconclusive. Across 8 experiments (6 dairy, 2 beef), this group of forage legumes had no effect on methane production (+1%), reduced methane yield (-7%, driven by positive effects on feed intake) and did not markedly affect methane intensity (+2%), when replacing grass or grass silage. Further meta-analysis and meta-regression is needed to explore variations in these overall responses.
- **Mitigation of methane production (g/d)**: no effect versus grass silage (based on *in vivo* experiments, dairy and beef)
- **Mitigation of methane intensity (g/kg milk or meat):** no effect versus grass silage (crude mean, *in vivo*, dairy and beef)

- **Time to reach average RL 8.** Opportunity to explore existing data to explain variation in effects on methane: minimum 2 years.
- **Co-benefits:** Saving cost and carbon through reduced need for inorganic N fertiliser. Biodiversity gain.
- **Costs:** Negligible.

16a-c. Forage adjustment – multispecies swards ('herbal leys')

- **Technology**. Multispecies swards typically contain several species of grass, white and other clovers, forb species such as chicory and plantain, and species (leguminous and non-leguminous) containing phytochemicals with potentially favourable effects on animal health (e.g., gut parasites) or emissions (nitrogen or methane). The class of phytochemical most often associated with lower methane is condensed tannins (CT), as found in birdsfoot trefoil (BFT), sainfoin, sulla and vetch.
- **User.** The challenge for users is the low yield, poor cold tolerance, and low persistency of some of these species.
- **Market, Societal.** General positive perception of other benefits of multispecies swards (e.g., drought tolerance, biodiversity, nitrogen fixation, soil health). Multispecies swards are a core component of 'regenerative' ruminant systems.
- **Regulatory approval**: no specific barriers.
- **Emissions reduction**. *In vitro* experiments have established the potential of both tanniferous species (e.g., BFT) and non-tanniferous species (e.g., chicory and plantain) to reduce methane production. Phytochemicals other than tannins may explain effects of chicory and plantain. Emissions measured *in vivo* will reflect the digestibility of each species, direct effects of phytonutrients, and effects on rumen kinetics. For example, chicory is known to accelerate rumen liquid passage rate, which may reduce the rumen population of methanogens. However, available *in vivo* data are inconclusive. Across six comparisons in four dairy experiments, consumption of a diverse multispecies sward (either grazed or zero-grazed) had trivial effects on methane production (+3%), methane yield (-1%) or methane intensity (+2%), compared with grass or grass/white clover controls. Of note is the low proportion of non-grass, non-clover species in the multispecies swards tested (with one exception, less than 35% of pasture DM). The exception is Wilson et al. (2020), who compared a grass/white clover with a pasture containing approximately 60% chicory and plantain. Cows grazing this mix produced 14% less methane, with 16% less methane yield and 8% lower methane intensity. Della Rosa et al. (2022) grazed relatively pure ryegrass and plantain pastures with non-lactating cows. Dry matter intake was lower for plantain, as was methane production (-23%) and methane yield (-15%). There is a need for further research

with multispecies swards with a high representation of species other than grass and white clover. There is also a need for further research to quantify effects of chicory and plantain, specifically.

- **Mitigation of methane production (g/d):** +3% to –15%, depending on proportion and species of non-grass forages (based on crude mean, i*n vivo* experiments, dairy).
- **Mitigation of methane intensity (g/kg milk or meat):** +2% to –10% (based on crude mean, *in vivo* experiments, dairy).
- **Time to reach average RL 8** Further research needed, followed by meta-analysis and meta-egression to establish predictive model, 3 years.
- **Co-benefits** Less reliance on inorganic N fertiliser, improved pasture productivity at shoulders of season, drought resistance, healthier soils, potentially improved animal health, biodiversity, and other ecosystem services
- **Costs.** Seed costs approximately 2x/hectare compared with perennial ryegrass.

17a-c. Forage adjustment - forage brassicas

- **Technology**. Forage brassicas such forage rape, kale, radish, turnips, and hybrids are low cost, fast growing annual forages, particularly useful as cover crops and break crops on mixed arable and livestock farms, and filling ‘summer gaps’ on livestock farms.
- **User:** Risk of soil and nutrient run-off during annual cultivation
- **Market, Societal**. General acceptance of forage brassicas as ruminant Regulatory approval. No specific barriers.
- **Emissions reductions**. Forage rape has significantly reduced methane emissions compared with grass. Across four comparisons in three experiments (two sheep, one dairy), forage rape reduced methane emissions by 17% and methane yield by 22%, with significant changes (lower pH, higher propionate) to the rumen fermentation. For example, see Sun et al. (2015).
- **Mitigation of methane production (g/d):** –15 to 20% (based crude mean, i*n vivo* experiments, sheep, and dairy).
- **Mitigation of methane intensity (g/kg milk or meat):** not known.
- **Time to reach average RL 8** At least two growing seasons to extend database and obtain missing information on methane intensity.
- **Co-benefits.** Productivity
- **Costs.** Allowing for wide variations due to choice of cultivation method (e.g., direct drill versus ploughing), lifetime of ley and use of fertiliser, annual growing costs are likely to be similar for forage rape and grazed grass. Use of forage brassicas can reduce costs of forage conservation, purchased feed, manure storage and housing. Additional labour may be required (e.g., movement of fences).

18a. Forage adjustment: management intensive grazing

- **Technology readiness**. 'Management Intensive Grazing' (MIG) is used here as a collective term to mean the adoption of some form of rotational grazing (rather than continuous grazing) with short-term decisions on stocking rate to manage average pre- and post-grazing herbage mass. Collectively, these decisions affect the quantity and quality (digestibility) of forage available to the grazing animal. Adoption of MIG is expected to improve the average quality of grazed forage, which may also increase intake. These effects are expected to increase methane production (g/d) but decrease methane yield (g/kg DMI) and intensity (g/kg milk or meat).
- With continuous stocking as a starting point, MIG practices include the adoption of some form of rotational grazing, supported by a range of methods (from visual assessment to direct measurement) to assess herbage availability and quality and support grazing decisions (i.e., who grazes where, and for how long). In general, implementation of MIG is likely to be more sophisticated on dairy than beef or sheep farms, with investment in technical infrastructure (permanent and temporary fencing, animal walking tracks) and regular monitoring of herbage biomass (e.g., rising platemeters).
- Best practice, and the physical technologies required to implement it, are the subject of continuing research and development in several countries in addition to the UK, notably Ireland, New Zealand, Australia, and southern South America. New technologies that could enhance MIG include the use of satellite or drone imagery to monitor herbage biomass and quality, and virtual fencing systems.
- **User readiness**. Many opportunities for knowledge exchange, including peer-to-peer learning are available.
- **Market**. The scope to increase the proportion of days per year spent grazing is, on average, greater for dairy than beef, and greater for beef than sheep. Several dairy processors are incentivising farmers to increase the number of grazing days, creating market pull for MIG.
- **Societal**. While there is a high degree of societal readiness for increased grazing, some groups may have misgivings or objections to some MIG practices, such as fencing practices deemed to be punitive, and the very visible high stocking densities involved in 'mob grazing'.
- **Regulatory**. There are no specific regulatory barriers to the adoption of MIG. The regulatory framework covering specific novel technologies relevant to MIG, such as virtual fencing and use of drones for pasture monitoring, is still evolving.
- **Emissions Reductions**. Because of heterogeneity of practice within the general category of MIG, and because the components of MIG are difficult to isolate, effects on methane parameters reported in available literature are quite variable.

The degree of emission reduction achieved by the adoption of MIG depends on what it is being compared with. Compared with continuous grazing, the limited data available for beef and dairy systems implementing some form of MIG show variable effects on emissions.

- There may be an important difference between sheep and cattle, due to their grazing behaviour. Savian et al. (2014) showed lower emissions per hectare, and a trend for lower emissions per kg growth, from sheep grazed continuously versus sheep grazed rotationally, which they attributed to the ability of sheep to select higher quality grass when allowed to graze a large area.
- **Time to reach average RL 8** As used here, MIG encompasses technologies already in widespread use (at RL 8 or 9), technologies used by early adopters (e.g., satellite imaging services, currently RL 4-6).
- **Co-benefits** Improved animal productivity (more precise matching of daily nutrient allowance to daily animal requirement), improved labour productivity.
- **Costs** Within this project we have not conducted an evaluation of costs of the various technologies that can be classified as MIG.

Conclusions

This report identifies the options for reducing methane emissions from beef, sheep and dairy livestock sectors, their current readiness and potential to deliver emissions reductions, the timescales, costs, and co-benefits to implementation. The tables below summarise the TRL for each readiness category for each technology, and the overall (averaged) TRL for the beef sector (Table 2a), the dairy sector (Table 2b) and the sheep sector (Table 2c).

Key points:

- For beef, sheep, and dairy sectors 'Forage adjustment – clovers and lucerne (alfalfa)', 'Forage adjustment – grass improvement - high sugar varieties', and 'Forage adjustment – maize and whole crop cereal silages' ranked within the highest averaged TRL (8) and were the only technologies that scored 8 for the sheep sector. However, the evidence shows only small reductions in methane, or the need for further research.
- For the beef and dairy sectors national genetic evaluations for production and feed efficiency, breeding for feed efficiency and use of sex semen are well established in dairy (TRL 8), the methodology to breed for feed efficiency exists for the beef and sheep sectors but with limited uptake due to costs involved in measuring feed intake and low use of AI (which also limits use of sexed semen).

- Methane reducing feed supplements are at various levels or readiness but are all limited by a lack of clear improvement in performance and no other incentives for their use.
- Breeding for methane emissions is limited by the cost of equipment to measure methane (e.g. respiration chambers and greenfeeds). The use of PACs is expected to accelerate selective breeding for reduced methane emissions in sheep. Microbiome driven breeding may emerge as the better option for beef and dairy.
- Direct air capture methods (GreenShed and halter devices) are at an early stage of development.

This report considers the implementation of these mitigation measures in isolation. When more than one measure is put into effect there will be an interaction between them, and so emissions reductions will not necessarily be cumulative. Interactions between mitigation measures have not been widely studied.

Table 2a: Summary table of innovations for the beef sector, listed by average readiness level

		Current readiness levels (1-9)					
Innov. No.	**Innovation**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Av. Readiness level**
15a	Forage adjustment – clovers and lucerne (alfalfa)	7	9	6	9	9	8
12a	Forage adjustment – grass improvement - high sugar varieties	6	9	6	9	9	8
14a	Forage adjustment – maize and whole crop cereal silages	7/8	9	6	8	9	8
6b	National genetic evaluations for production and feed efficiency	8	6	7	8	9	8
16a	Forage adjustment – multispecies swards ('herbal leys')	6	7	6	9	9	7
5a	Feed supplements: Mootral	6	8	6	7	9	7
6a	Breeding for feed conversion efficiency (within breeds and/or commercial breeding companies)	8	6	6	8	8	7
9a	Sexed semen	7	6	6	8	8	7
17a	Forage adjustment - forage brassicas	6/7	6	6	8	9	7
8a	Microbiome-driven breeding for methane mitigation	7	7	6	7	7	7
3a	Feed supplements: Silvair	8	8	6	2	9	7
4a	Feed supplements: Red seaweed (Asparagopsis)	6	8	2	7	9	6
2a	Feed supplements: Agolin Ruminant	6	8	3	9	4	6
1a	Feed supplements: Bovaer 10	8	8	3	4	6	6
10a	CH_4 direct air capture - GreenSheds	5	7	5	4	6	5
11a	CH_4 direct air capture - halters	5	7	2	4	9	5
7a	Breeding for methane mitigation using respiration chamber measurements	5	3	3	7	5	5
13a	Forage adjustment – grass improvement - high lipid grass	4	7	4	2	2	4

Table 2b: Summary table of innovations for the dairy sector, listed by average readiness level

		Current readiness levels (1-9)					
Innov. No.	**Innovation**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Av. Readiness level**
6d	Breeding for feed efficiency (within commercial breeding companies)	8	8	8	8	9	8
6e	National genetic evaluations feed efficiency	8	8	8	8	9	8
9c	Sexed semen	9	7	8	8	8	8
15c	Forage adjustment – clovers and lucerne (alfalfa)	7	9	6	9	9	8
12c	Forage adjustment – grass improvement - high sugar varieties	6	9	6	9	9	8
14c	Forage adjustment – maize and whole crop cereal silages	7/8	9	6	8	9	8
5c	Feed supplements: Mootral	7	8	6	7	9	7
16c	Forage adjustment – multispecies swards ('herbal leys')	6	7	6	9	9	7
17c	Forage adjustment - forage brassicas	6/7	6	6	8	9	7
7c	Breeding for reduced methane emissions	7	7	6	7	7	7
3c	Feed supplements: Silvair	8	8	6	2	9	7
4c	Feed supplements: Red seaweed (Asparagopsis)	5	8	2	7	9	6
8c	Microbiome-driven breeding for methane mitigation	5	7	5	7	7	6
1c	Feed supplements: Bovaer 10	8	8	3	4	7	6
2c	Feed supplements: Agolin Ruminant	6	8	3	9	4	6
11c	CH_4 direct air capture - halters	5	7	2	4	9	5
10c	CH_4 direct air capture - GreenSheds	3	7	2	4	6	4
18a	Forage adjustment: Management Intensive Grazing	4-8	5-7	4-7	5-7	3-8	4
13c	Forage adjustment – grass improvement - high lipid grass	4	7	4	2	2	4

Table 2c: Summary table of innovations for the sheep sector, listed by average readiness level

		Current readiness levels (1-9)					
Innov. No.	**Innovation**	**Technology**	**User**	**Market**	**Societal**	**Regulatory**	**Av. Readiness level**
15b	Forage adjustment – clovers and lucerne (alfalfa)	7	9	6	9	9	8
12b	Forage adjustment – grass improvement - high sugar varieties	6	9	6	9	9	8
14b	Forage adjustment – maize and whole crop cereal silages	7/8	9	6	8	9	8
16b	Forage adjustment – multispecies swards ('herbal leys')	6	7	6	9	9	7
5b	Feed supplements: Mootral	5	8	6	7	9	7
17b	Forage adjustment - forage brassicas	6/7	6	6	8	9	7
4b	Feed supplements: Red seaweed (Asparagopsis)	6	8	2	7	9	6
6c	Breeding for feed conversion efficiency	7	6	4	6	8	6
2b	Feed supplements: Agolin Ruminant	5	8	3	9	4	6
7b	Breeding for reduced methane emissions	8	5	4	6	5	6
1b	Feed supplements: Bovaer 10	6	8	3	4	6	5
3b	Feed supplements: Silvair	2	8	2	2	9	5
8b	Microbiome-driven breeding for methane mitigation	5	4	5	4	5	5
13b	Forage adjustment – grass improvement - high lipid grass	4	7	4	2	2	4
10b	CH_4 direct air capture - GreenSheds	2	6	2	2	6	4
9b	Sexed semen	2	1	1	6	4	3

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