Reducing emissions from agriculture – the role of new farm technologies

A report for Agricultural Policy Division

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Authors: Andrew Barnes[*1], Jenna Bowen[2], Gemma Miller[2], Kaia Waxenberg[3], John Newbold, Carol-Anne Duthie[2], Bob Rees[4], Vera Eory[1], Rainer Roehe[2], Jos Houdijk[5], John Farquar[3]

[1] Rural Economy, Environment and Society Department, SRUC
[2] Beef and Sheep Research Centre, Agriculture, Horticulture and Engineering Sciences, SRUC
[3] SAC Consulting
[4] Carbon Management Centre, SRUC
[5] Monogastric Science Research Centre, SRUC
[6] Climate Emergency Challenge Centre, SRUC

**Main contact: Andrew.Barnes@sruc.ac.uk*

Executive summary

Scotland and Greenhouse Gases in Agriculture

The Scottish Government has committed to reaching net zero emissions by 2045. The Scottish Government's Climate Change Plan update[1] requires the equivalent of a 31% reduction in agricultural emissions by 2032 from 2018 levels. Between 1990-2019 Scottish agriculture's emissions decreased by only 13%. The uptake of new technologies and practices provides a means to meet reductions in greenhouse gases (GHGs) whilst balancing the need for food production.

A number of studies have identified a range of practices and technologies which would support progress to this goal, and their cost-effectiveness and impact have been assessed through the Marginal Abatement Cost Curve. The purpose of this project is to identify and explore technologies which have not currently been considered and evaluated for Scotland but which may provide additional carbon savings. It is important to note that the scope of this report does not include nature-based practices but is focused on new technological development that may be applicable to farms in Scotland. Moreover, we take a time frame of 20 years as the horizon by which new technologies could be feasibly developed and adopted to impact Scotland's Net Zero goal.

Identifying New technologies for Scottish Agriculture

Using expert knowledge, state of the art literature reviews and scrutiny of patents databases we identify a 'long list' of 86 new technologies and technology areas which may be applicable to Scottish agriculture if they were developed further and trialled within the Scottish context.

These new technologies cover a range of areas, including feed additives directed at enteric methane, remote sensing technology and associated monitoring and data analysis to support control and management of input resources. In addition, this also includes the replacement of traditional materials with more sustainable components, e.g. single cell proteins grown from algae. Moreover, technologies which have evolved from non-agricultural sectors, e.g., distributed ledgers, 3D printing were also identified as offering potential. To produce a short list all technologies were scored against a range of criteria. This produced a list of 13 technologies or technology areas which are worth exploring further (Shown in Table E1).

Measuring the potential of candidate technologies

This short-list was explored in greater detail to understand the GHG potential of these technologies, their current stage of development, their potential on-farm cost and further barriers to implementation. For most technologies, the estimates of GHG savings range

[1] The update to Scotland's 2018-2032 Climate Change Plan sets out the Scottish Government's pathway to new and ambitious targets set by the Climate Change Act 2019

quite considerably and are typified by only limited evidence of application from mostly non-Scottish contexts, for instance asparagosis (a feed additive based on seaweed) has been found to reduce methane emissions by 56% in beef cattle, but this relates to a single trial in another country. Accordingly, any estimates of GHG saving and their cost of implementation are difficult to generalise and come with large uncertainties.

These technologies are shown in Table E1, identifying their potential for GHG saving, the uncertainties around these estimates, the expected time to market, main barriers and suggested implementation pathways. It is also notable that the highest ranked technologies focus on solutions for the livestock sector. This is mostly because of this sector offers the most potential in saving GHGs.

Table E1. Summary of technologies and findings towards their applicability to Scottish farming

Measures Applicable to tillage and grassland

Name	Description	Potential for GHG Saving[2]	Uncertainties	Expected Time to market	Main Barriers	Implementation Pathway
Rock dust	Application of crushed, reactive silicate rocks (such as basalt)	Abatement potential by agricultural soils in the UK has been estimated between 0.2 and 0.8 CO_2 per tonne of basic rock (though not currently tested on temperate soils)	Sequestration potential will vary depending on the chemical composition of the rock material.	3 years	Cost of product; Regulatory Compliance	More testing/trialling for on-site conditions to prove efficacy
Biochar	Carbon rich, pyrolysis of organic waste	UK studies estimate an abatement potential of 0.7-1.4 t CO_2eq/ oven dry tonne	Total GHG abatement will vary depending on organic feedstock, production technology, and predicted effects on crop yields.	1-5 years	Availability of feedstock; Regulatory compliance; Lack of efficacy; High capital costs	Support high capital costs for development of marketable product and spreading equipment

[2] It is notable that these estimates will not take into account the full life-cycle of emissions, specifically the indirect emissions from, e.g. more computer processing, importing raw materials from abroad etc.

Measures Applicable to tillage and grassland (continued)

Name	Description	Potential for GHG Saving	Uncertainties	Expected Time to market	Main Barriers	Implementation Pathway
Underground Sensors	Soil sensor system distributed under turf	Unknown	No study on underground sensors and GHG savings exist	1-3 years	High capital cost plus subscription-based services for data analysis	Grants for developing open source platforms to make metrics more useful.
Cloud-based bioinformatics	Cloud platforms to link genomic discoveries to plant breeding decisions	Unknown	Only supports GHG reduction indirectly	1-5 years	Lack of infrastructure	Encouragement of skills and training in metrics through training/degrees.
Biological nitrification inhibitors	The natural ability of certain plant species to release nitrification inhibitors.	Trial in New Zealand found reduced nitrous oxide emissions by 50% for the use of plantain within species rich swards.	The mechanism of this effect is not entirely clear	5-10 years	Regulatory compliance; Lack of evidence	More public funded research to trial and measure impacts in field conditions.

Measures applicable to livestock production

Name	Description	Potential for GHG Saving	Uncertainties	Expected Time to market	Main Barriers	Implementation Pathway
Feed Supplements (Seaweed)	Asparagosis.	An estimated reduction of 56% in methane emissions in the beef sector, a reduction of 22% in the dairy sector and 53% in the sheep sector.	Only a small number of trials in the US and Australia	5-10 years	Limited availability of non-native product; Lack of infrastructure; Regulatory compliance on iodine in foods	Authorities could change the way seaweed as a methane mitigator is regulated in the EU.
Other Feed Supplements	Monesin, Vegopils, Coconut oils etc.	Monesin has been found to reduce methane emissions by 2.9% (for a study in Canada)	Only estimates for Monesin relate to single trial	1-15 years	Lack of efficacy; lack of data on interactions; lack of infrastructure; regulatory compliance; lack of financial rewards for manufacturers	Regulatory and financial incentives; Trialling and demonstration on the effect of combinations of feed additives.
Microbial proteins	Yeast; Microalgae-based feed; Bacteria-extracted feed; Fermentation-based feed	Unknown	Considered as a replacement for soya-based meal and would be carbon off-setting.	3-5years	Technical barriers towards scaling up production	Regulatory or tax interventions could be considered, e.g. for replacing soya-based meal, may encourage innovation and adoption.

Measures applicable to livestock production (continued)

Name	Description	Potential for GHG Saving	Uncertainties	Expected Time to market	Main Barriers	Implementation Pathway
Genetic profiling/Genomic testing in breeding programme	Marker assisted management (MAM); . Marker-Assisted Backcrossing	Equivalent to an up to 8% reduction in methane emissions per year.	Trials conducted in Scotland	5-10 years	Lack of infrastructure; Costs of sampling and storage	Establishing test stations - similar to Beef Efficiency Scheme - to prove efficacy.
Fluoride and tannin additive to manure	The additive consists of the two naturally occurring substances fluoride and tannins	In pigs: 95% reduction in ammonia emissions, 99% reduction in methane emissions, and 50% reduction in odour.	Studies at lower dosages have not identified any emission reductions.	10-15 years	Cost of product: Regulatory compliance; Low evidence base	Support development work on demonstrating efficacy; Providing a source for usable tannins for the supply chain

Measures applicable to livestock production (continued)

Name	Description	Potential for GHG Saving	Uncertainties	Expected Time to market	Main Barriers	Implementation Pathway
Methane Vaccine	Aims to introduce antibodies into a cow's saliva	Efficacy ranged from 7.7% to 69% methane reduction	Multiple studies were unsuccessful *in vivo.*	10 years	Lack of efficacy; regulatory compliance	Lack of testing in Scotland. Trials could be set up to prove/disprove efficacy
Smart Cattle sheds	Closed sheds with monitoring system	Conservative estimate for a beef finisher is 14-25% reduction per year in tCO^{2}e	A specific trial was conducted in Scotland. This would limit uncertainties for application across Scotland	5-10 years	Cost of product; Lack of infrastructure and rural broadband.	Targeted support for capital restructuring on farm may encourage more adoption
Connected animal mounted sensors	Monitoring of feed intake, and automated weigh crates	Beef: reduced both total farm emissions (2.4% - 7.4%) and emission intensities (1.5% - 11.9%); Dairy: showed reductions in whole farm emissions (0.4% - 0.9%) and all scenarios reduced emissions intensities (3.0% - 9.0%).	Modelled on a Scottish farm. This would limit uncertainties for application across Scotland	On market	Cost of product; Lack of infrastructure and rural broadband.	Financial training and support around return on investment and payoffs

Overall Conclusions

A range of new technologies are available.

There are multiple technologies and technology areas which have not currently been considered in detail within the context of Scotland's requirement to meet net zero emissions by 2045. Whilst we explored 13 of these technologies in detail to understand their potential for GHG saving, their on-farm adoption and the barriers to development, this does not exclude the 'long-list' from further investigation.

A small number of technologies are strong candidates for accelerated development.

We find the most likely candidates for further intervention to be:

- **Feed additives** are both easily implemented on-farm and target enteric methane production, the most significant greenhouse gas from Scottish agriculture. Development, testing and trialling can be part of Government intervention. Notably, however, a key issue is the need for regulatory approval to ensure these additives are safe for human and animal consumption. In addition, exploring the relationship between combinations of feed additives would offer some value in understanding how these may improve or negate the methane reducing effect.
- **Rock dust.** This product seems to show potential for reducing nitrous oxide emissions across arable land and potentially has positive spinoff effects for dealing with construction industry waste. However, issues around application rates and toxic components of rock dust applied to agricultural land would need to be resolved and this could be through applied testing and analysis within the Scottish context.
- **Microbial Proteins.** The attraction of these proteins would be as an alternative to imported soya meal, which constitutes a large part of livestock diets. These are also rolled out to high value sectors, with little work on cattle and sheep systems. There are technical barriers to scaling up production, hence further investment into development of ways to produce these proteins could be a way to overcome these scaling issues and create cost-effective alternatives for the sheep and cattle sector.
- **Animal mounted sensors.** These target animal health, which is a significant intervention that could reduce GHG emissions from livestock. Whilst the production and supply of sensors is supported through commercial development, there are high costs to adoption, as well as the need for training and demonstration to operate these systems at their optimal levels. Hence, support for capital investment may be justified under new tranches of a replacement agricultural policy, both for supporting investment but also for establishing best practice in operating sensors.

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List of Abbreviations

3-NOP	3-Nitrooxypropanol
AI	Artificial Intelligence
BNI	Biological Nitrification Inhibiters
CAP	Common Agricultural Policy
CO_2	Carbon Dioxide
EU	European Union
IoT	Internet of Things
LORA	Low power, long range wireless
MAB	Marker Assisted Backcrossing
MACC	Marginal Abatement Cost Curve
MAS	Marker Assisted Selection
N_2	Nitrogen
N_2O	Nitrous Oxide
nano-TiO_2	Nanometer-sized titanium dioxide
NGS	Next Generation Sequencing
SCP	Single Cell Proteins
TA-NaF	Tannic Acid with Fluoride

1.0 Introduction and Background

Agriculture represented 16% of Scotland's emissions in 2018[3]. The Scottish Government has committed to reaching net zero emissions by 2045, including a reduction of 75% by 2030. The Scottish Government's Climate Change Plan update[4] requires the equivalent of a 31% reduction in agricultural emissions by 2032 from 2018 levels. Between 1990-2019 Scottish agriculture's emissions decreased by only 13%.

Recent work on marginal abatement cost curves (Eory et al., 2022) presents a number of areas which, if adopted at scale, would support progress towards the net zero target in 2045. These technologies offer a feasible set of solutions which could be adopted for farming at a range of costs for on-farm adoption. As these effects and costs are reasonably well tested then more certainties can be placed on their potential if adopted by industry. These technologies, studied in the MACC for Scotland are shown in table 1.

[3] The Devolved Administration GHG Inventory 1990-2019

[4] Securing a green recovery on a path to net zero: climate change plan 2018–2032 - update

Table 1. MACC mitigation measures

Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ (t $CO_2e)^{-1}$
Grass-legume mix	52	-1,044
Variable rate nitrogen	19	-628
Current breeding goal in dairy	39	-426
Genomics breeding dairy	58	-446
Genomics breeding beef	7	-432
Health dairy	11	-381
Lower emission breeding goal dairy	32	-339
AD pig poultry	10	-274
Soil compaction	2	-255
Health sheep	39	-244
AD cattle	30	-184
Lower emission breeding goal beef	8	-356
Health beef	25	-2
Slurry acidification dairy	32	-1
Faster finishing beef	66	0
Increasing beef calving rate	29	0
Reducing beef calving interval	4	0
Sexed semen in dairy	71	0
Soil pH	17	17
Slurry acidification beef	42	28
Impermeable slurry cover dairy	10	34
Impermeable slurry cover beef	9	36
Nitrate feed additive beef	119	38
Grain legumes	18	76
Slurry acidification pigs	2	84
Nitrate feed additive dairy	22	84
3NOP dairy	30	85
Cover crops	33	110
Impermeable slurry cover pigs	0	122
Nitrate feed additive sheep	4	196
3NOP beef	51	226
Nitrification inhibitor	18	319
High fat diet beef	13	504
Urease inhibitor	2	518
High fat diet sheep	6	909
High fat diet dairy	1	3,395
Total	931	

Source: Eory et al. (2022

These technologies were also further explored with Farmer Led Groups which suggests that future policy has to recognise technologies which are both cost-effective to adopt and attractive for the farmer[5].

2.0 Purpose and Scope

The purpose of this research is to horizon scan and seek to identify new emerging approaches - those not identified in the MACC. This is composed of technologies, practices and improvements with the potential for technological advances to support net zero goals but which also do not penalise food production. Hence, it seeks to understand the opportunities these approaches may present for Scotland to reduce agricultural emissions while continuing sustainable food production.

The scope of this project is to focus on those technologies which can be adopted at the farm level. However, we take a flexible approach, for example whilst disruptive consumption technologies such as growing meat from animal cells, so called 'clean meat', will affect farm production we do not foresee this technology significantly affecting production up to 2045. However other technologies, for example 3D printing of food sources, could be seen as a viable on farm alternative as a source of both feed production and bioplastics from algae cells.

Whether these technologies would need significant investment to enable this technology is considered after the original horizon scan. Moreover, we focus on technologies that support or improve food production, so we do not concern ourselves with technologies whose sole purpose is to produce energy from waste. Significantly, we also ignore nature based, regenerative solutions, such as, for example, silvo pastural systems. We expect these to be part of any solution towards net zero for Scottish agriculture. Accordingly, our scope is on purely technological advances which have the potential for farm adoption within the time frame of the next 20 years that are worth exploring for their GHG potential and could be feasibly adopted. This includes technologies that have been proposed, being trialled, are near-market or are currently introduced but are currently niche in this or other countries.

Accordingly, the project has three main research objectives, namely:

i) to horizon scan those approaches which could come to market within the next two decades which will provide significant GHG reductions whilst not penalising food production,

ii) to quantify the impact of these approaches on GHG reduction when applied to the Scottish farming sector as well as, where possible, the supply chain itself,

iii) to identify the implementation pathway of candidate approaches to bring these approaches to adoption.

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[5] Farmer-led climate change groups

2.1 Foresight for agriculture and Agriculture 4.0

A number of recent documents have heralded the future of agriculture as a new technology frontier, similar to the so-called green revolutions of the 1960s. The rationale towards this leap is due to technological progress in the last two decades, such as advances in artificial intelligence, machine learning, and companion technologies around sensing and real time data gathering. This is combined with concerns over the GHG burden of current methods of production, drops in efficiency gains due to growing disease and pest resistance in crops and animals, but also an increasingly scarce or volatile input base. Effectively traditional technologies, around crop and livestock breeding, are being complemented by the oppourtunities that large-scale data collection and innovations from other sectors could bring.

The next phase of technology development - known as Agriculture 4.0. - has merited a significant focus in policy and academic circles (De Clerq et al., 2018[6]). This provides a general ethos for identifying the scope for technological solutions for future on-farm food production and current and future market growth. A figure to illustrate this is provided in Figure 1.

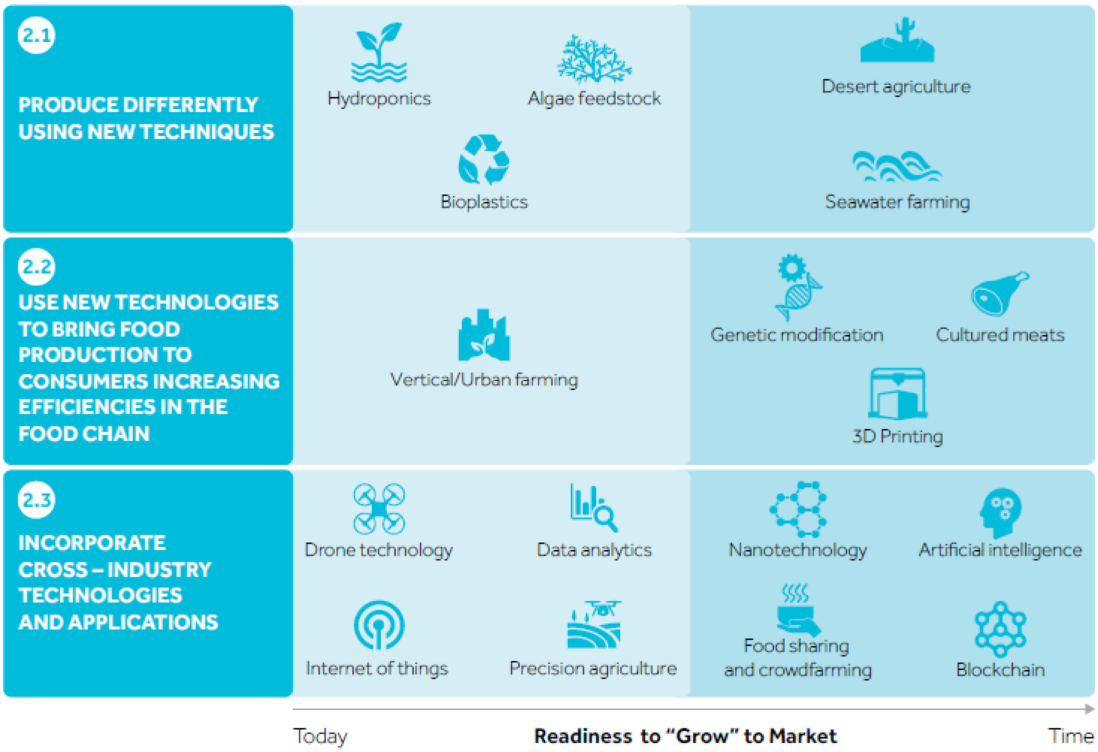

Figure 1. Agriculture 4.0. The figure shows a typology of technologies that can be employed for future farming approaches. These are presented in terms of both technologies which are available now and technologies that could be employed in the future. (Source: De Clerq et al., 2018).

[6] De Clercq, M., Vats, A., & Biel, A. (2018). Agriculture 4.0: The future of farming technology. *Proceedings of the World Government Summit, Dubai, UAE*, 11-13.

This specifies three approaches which could be used to support the horizon scanning aspect of this report:

1. **Produce differently with new techniques**, on-farm examples would include the development of new feed additives and the replacement of diesel with hydrogen or electric vehicles.
2. **New technologies for increasing efficiencies in the food change,** on-farm examples would include using 3D printing technology to tailor feed supplements, or use of UAVs to spread nutrients or seed.
3. **Incorporate cross platform technologies,** on-farm examples tend to focus on 'smart farming solutions'. This brings technology from other industries or connects a series of technologies to provide a farming system based on extensive data collection and analysis to improve decision-making (Figure 2).

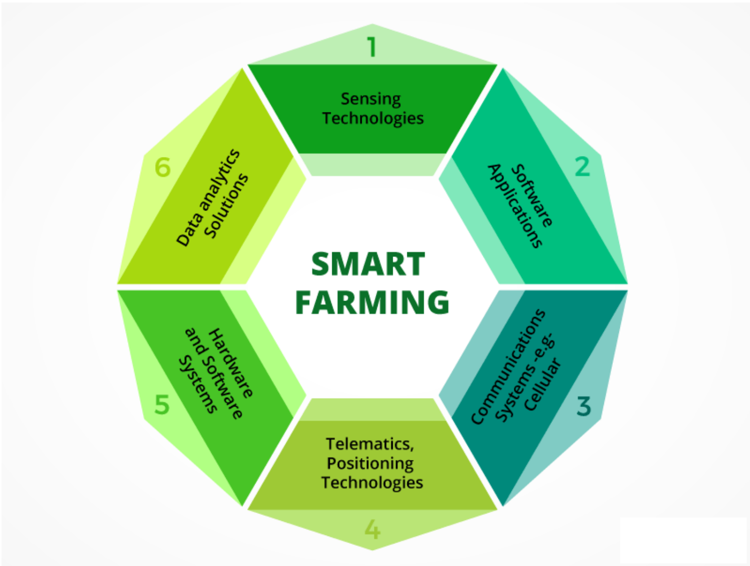

Figure 2. Technologies which composed smart farming. The figure shows different technologies that are needed to support a transition to more connected agricultural systems. (Source: Great Pyramid)

Generally, therefore when we define new agricultural technologies, we need to consider both those products which evolve from older products, e.g., new feed additives, but also those which offer potential and may be applied from different industries, e.g., smart monitoring for office buildings.

2.2 What can feasibly be adopted within the next 20 years?

The above section provides a general framework in which technologies may emerge over the next two decades for adoption at farm level. We define our technology for inclusion in terms of a 20-year period, specifically to identify technologies that could be adopted which would affect GHG saving for net zero in 2045.

Figure 3 shows the three main stages of technological development - taking a linear approach to innovation and invention. Firstly, we can identify products that may have already been introduced into the market internationally or adopted by a small niche of farmers within Europe. We can then define near market technologies as those at or near launch into the market. Finally, there is the realm of applied research and development. This covers technologies which will have passed internal testing and developed into a coherent idea beyond patent level (applied research) and where effort is being directed towards developing a marketable product (development). The figure below shows these pathways to itemise our technologies.

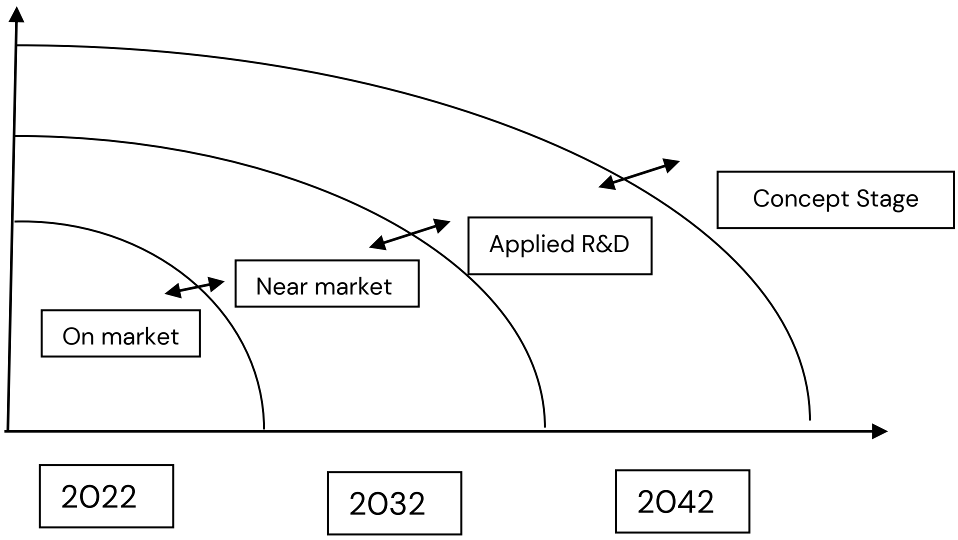

Figure 3. Time frame for the introduction and stages of technology development. The figure shows the time frame considered for this report.

The time to market varies, with for example new crop varieties taking 7-10 years of trials before they are released, or feed additives requiring a series of regulatory approvals before their introduction into the UK market. Consequently, within the time frame of 20 years, biological/medical products will be slowed by these institutional processes. Here we show the criteria by which we define our search for inclusion.

- **On-Market**: This is technology which has been introduced, either in another country or a different context, e.g., domestic buildings, which can be applied to on-farm production.
- **Near-Market:** Those technologies where there has been significant development and would be launched within the next 10 years.
- **Applied Research and Development**: Those technologies at concept or single trial and testing stage where significant development would launch them within the next 20 years.

3.0 Methodology

3.1 Identifying the candidate approaches

3.1.1 Technologies at the farm level

Our current farm systems are composed of livestock, cropping, horticultural and mixed farms. These range from highly extensive enterprises - exemplified in upland sheep farming systems - to highly intensive fruit production. Current efficiency levels vary within these farm types and, whilst productivity is growing, those farms at the frontier are adopting improved varieties, or using genetic selection indices to promote herd productivity.

The major food producing components of Scottish farming is comprised of several functions, e.g., land management, livestock management etc. To provide a schema for categorising new technologies we identified a set of sub-functions that the technology would aim to target for the farm. These are shown in the schema below.

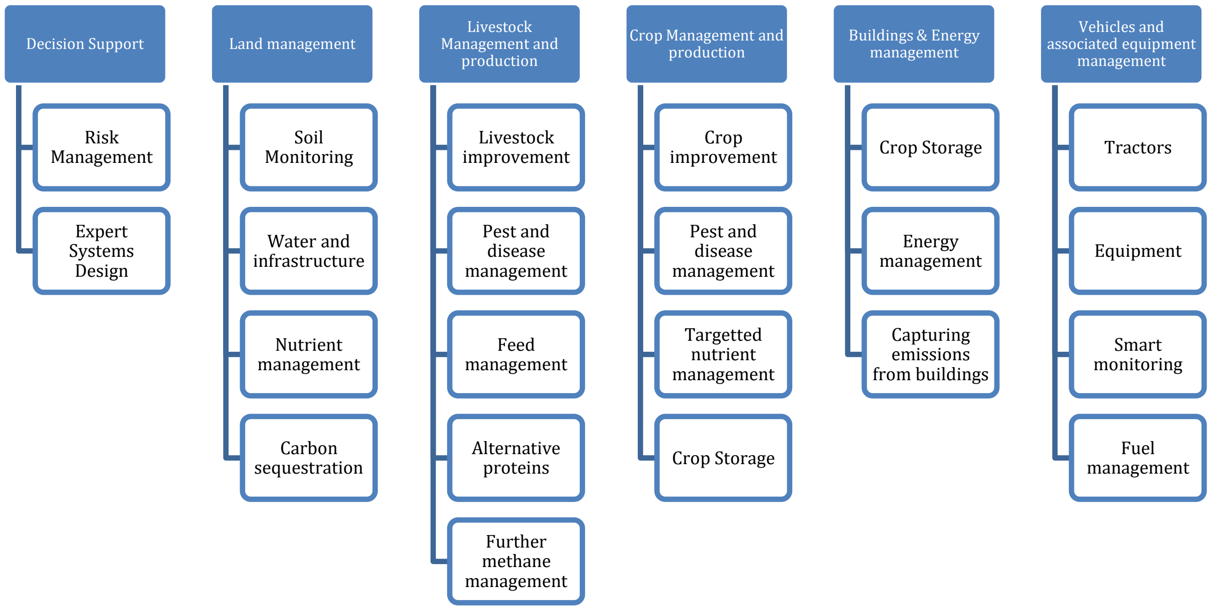

Figure 4. Schema for understanding farm functions and potential routes for technology improvement. The figure shows the main functions which all support food production that could be improved to reduce greenhouse gas emissions.

One of our assumptions is that farms and their functional structure will remain the same over the next twenty years. Whilst there may be disruptive technologies that reform our current farm structures over this period, the institutional frameworks, e.g., land tenure, and proposed policy support schemes would, we argue, have a greater influence on disruptive change. Hence, any reconfiguration of farming functions is beyond the realm of this report.

3.2. Description of the Long List

Given the above criteria we explored a number of routes to identify new technologies. Expert knowledge and engagement with the commercial sector within the research group identified new technology that has been introduced elsewhere or is in development with major commercial producers. The patent literature was also explored using the schema of

Figure 4 as a guide, e.g. 'livestock improvement technologies', with a view to identifying viable patents that infer applied technologies. This was achieved through patent searches using International Patent Office (IPO)/Ipsum, European Patent Office (EPO)/Espacenet, United States Patent and Trademark Office (USPTO) and GooglePatents. Finally, for several areas, we conducted reviews of the literature to assess the current state of these technologies, e.g., single cell proteins. Accordingly, whilst the search was not strictly systematic the expertise in the group covered these functions which were supported by literature and patents that define new technologies in these areas. What follows are brief descriptions of the long list. This is presented against the schema above in terms of the farm's functions and functional areas by which the technology is targeted.

3.2.1. Decision Support

Risk management

- *Distributed Ledgers (D1):* Blockchain and distributed ledger technology (DLT) have the potential to increase efficiency, transparency, and trust throughout agricultural supply chains. Blockchain for food supply chain can empower all market players by building relationships of trust. Will offer oppourtunities for transparency for crop/livestock insurance. This will increase stability of incomes and therefore planning.
- *Weather Tracking(D2):* Brings in the oppourtunity to link real time data and forecasting for crop yield. Forecasting is based on a variety of machine learning or AI methods to improve robustness. This will improve planning for yield stability. This will lead to technological advancements such as online services and connected apps (in vehicles etc.)

Expert systems

- *Low-cost infrastructure (D3):* Functional tech to link up sensors and data analytics etc. Low cost and low power, wireless mesh network, this makes it attractive for application. Currently used in smart homes but has potential to field based sensor systems. Products would include a low-cost, low-power, wireless mesh network.
- *Digital twinning (D4):* Use of artificial intelligence coupled with sensor input to mimic a farm set up. Supports decision making to optimise solutions for resource use under uncertainty. Part of a 'SMART farm' assemblage.

3.2.2. Land Management

Soil Monitoring

- *Moisture Sensors (L1):* Wireless sensors networked to detect moisture/warn of changes in moisture. Not adopted in Scottish agriculture but may be more relevant under increasing drought in the East.
- *Underground Sensors (L2):* Soil sensor system distributed under turf. This is currently applied in golf and sports course care but has the potential for applying under land for intensive grazing.

Water Management

- *Substrate Sensors (L3):* Analysis of soil and moisture within a single sensor. Currently applied in greenhouse conditions.

Nutrient Management

- *Biochar (L4):* Carbon rich, pyrolysis of organic waste - found to mitigate carbon and support productivity - mostly applied in developing countries with uncertain application in temperate countries.
- *Rock dust (L5):* Application of crushed, reactive silicate rocks (such as basalt) found to offset fossil fuel CO_2 emissions. Only tested in tropical agriculture but has potential for temperate soils.
- *Combined application of nitrification inhibitors with urea and urease inhibitors with deep placement (L6):* Combines nitrification with urea inhibitors. Deep placement in soil has been found in experiments to reduce N^2O and ammonia.
- Engineered soil microbes (L7): Advanced synthetic biology coupled with large data sets. This aims to deliver biological traits which target nitrogen fixation and thus reduce N^2O emissions.

Carbon Sequestration

- *Methane oxidation in soil (L8):* Opportunity to feed flue gases from barns into underground pipes that allow oxidation of methane by soil microbes. Biological treatment methods are already common in the pig farming industry and can be adapted to methane removal if the issues around N^2O generation can be resolved.

3.2.3. Livestock Management and Production

Livestock Improvement

- *Genetic profiling/Genomic testing in breeding programme (Liv1):* Genetic tests can be used to manage groups of cattle. Tests can give producers a better idea of how animals will perform in specific situations. These tests enable producers to sort animals into particular management groups. This is commonly referred to as marker assisted management (MAM).
- *Genetic profiling/Genomic testing in breeding programme (Liv2):* Marker-Assisted Backcrossing. The goal of backcrossing in commercial agriculture applications is to move a single trait of interest—such as drought tolerance, high productivity, or disease resistance—from a donor parent to progeny. Marker-assisted backcrossing using Illumina microarrays or Next generation sequencing (NGS) enables researchers to monitor the transmission of the trait gene via a genetically linked marker that can be easily screened. This process significantly accelerates backcrossing programs and reduces the time to release of commercially viable plant lines.
- *Tail Mounted Sensors (Liv3):* Measures tail raising in animals, as accelerometers, fed to monitors for fertility measurement. Can be coupled with machine learning to forecast fertility, predict calving and detect potential health issues.
- *Use of milk spectral data to predict new and existing phenotypes routinely (Liv4):* Mid-infrared spectroscopy is based on crossing matter by electromagnetic radiation. MIRS (Mid infrared spectroscopy) has been tested to predict new milk phenotypes of economic relevance such as fatty acid and protein composition, coagulation

properties, acidity, mineral composition, ketone bodies, body energy status, and methane emissions.
- *Use of digital images to predict new phenotypes (Liv5)***:** Sequencing and other omics technology facilitate deep phenotyping of livestock at the molecular level. Combines 'big data' collection with algorithms for high throughput.

Pest and disease management
- *Automated heat detection system (Liv6):* The rumen bolus measures direct values with the highest accuracy inside cattle, in the reticulum. The boluses are administered once and are completely maintenance-free.
- *Connected animal mounted sensors (Liv7):* Animal mounted sensors (pedometers, ear-tags, collars) record activity, feeding times, temperature, rumination - deviation of which can indicate ill-health.
- *Visual Movement sensing (Liv8):* Movement mapping to identify lameness and raise productivity - use of digital images to identify differences in behaviour.
- *Digital pathology and computational image analysis (Liv9):* Using computer images of samples, combined with large-scale data analysis to predict incidence of disease.

Feed management

Feed Supplements (aimed at reducing methane)
- Seaweed. The last decade studies explored the potential. Though only recently experienced commercial development (liv10)
- Agolin® Ruminant (Agolin SA, Bière, Switzerland) is a commercially available pre-mixture of flavourings. The main active compounds of this product are food grade and chemically defined plant extracts including coriander (Coriandrum sativum) seed oil (up to 10%), eugenol (up to 7%), geranyl acetate (up to 7%) and geraniol (up to 6%) along with some preservatives such as fumaric acid. (liv11)
- Mootral (garlic-oil based methanogenesis inhibitor) (liv12)
- Standardized combinations of active substances naturally occurring in aromatic plants and spices, selected for their proven in-vivo effects (liv13)
- Yucca extract; Quillaya extract; Tea seed extract; Sapindus extract (liv14)
- Unsaturated veg oils; Coconut oil (liv15)
- Monensin – commercially available product(liv16)
- Condensed & Hydrolysable tannins (liv17)
- Disodium fumarate & malate (liv19)
- Pyruvate carboxylase inhibitors (liv20)
- Calcium nitrate (liv22)
- Biochar as a feed additive (liv23)
- Glycerol monoester of lauric acid (liv24)
- Chinese red yeast rice (statins) (liv27)
- Solid-state fermentation of straw and other crop residues (liv28)
- N-alkyl-pABA derivatives (liv29)
- Peptide from *L.lactis* fermentation (liv30)

- Essential oils (cashew nut oil) (limonene)(peppermint oil) (liv31)
- Mustard oil; Sandalwood oil(liv32)
- Rhubarb (9,10-anthraquinone) (liv33)
- Bile acids are bio-surfactants and assist intestinal digestion and absorption of lipids and fatty soluble vitamins such as Vitamin A, D, E and K, and improve nutrient utilisation (liv34)
- MetaSmart® anester of the analogue of methionine, is a unique feed ingredient and patented molecule from Adisseo. (liv35)
- Use of cultures to produce fermented feed substances (liv36)
- Monitoring of feed intake, and automated weigh crates combined with 3D cameras is an important management tool - less efficient animals generally producing more methane. (liv37)

Alternative proteins

Microbial proteins
- Yeast (liv38)
- Microalgae-based feed(liv39)
- Bacteria-extracted feed(liv40)
- Fermentation-based feed(liv41)

On-farm Insect production
- Currently produced at a small scale; there seem to be few barriers for production at farm level aside from cost of production. Zero waste Scotland produce guidelines of production. (liv42)

3D feed printing - algae for protein
- Algae can be used to derive balanced feeds targeting methane etc. Also, early-stage bioplastics for silage bales (liv43)

Further Methane management
- Fluoride and tannin additive to manure: The additive consists of the two naturally occurring substances fluoride and tannins, has the potential to drastically reduce emissions of various gases from manure, while at the same time reducing odours by 50% (liv44)
- Methane mask for cattle: Mask placed on cattle to capture methane expelled. This methane is oxidised (liv45).
- On-farm fertiliser production from manure with plasma technology: Using electricity atmospheric N2 is converted to nitrate and mixed with manure to make ammonium-nitrate, preventing ammonia losses and enhancing the fertiliser value of the manure (liv46).
- Methane Vaccine: Aims to introduce antibodies into a cow's saliva which then pass to the animal's rumen or stomach and bind with the methanogens which convert hydrogen to methane. There is no conclusive evidence of its efficacy but could be a future technology. Focus so far has been on dairy cows(liv47).

3.2.4. Crop Management and production

Crop improvement

- *Mini-chromosomes (Crop1):* A mini-chromosome is a tiny structure containing a cell that can add dozens of traits to a plant without altering its original chromosomes. This could result, for example, in drought tolerance and nitrogen use efficiency. It is not considered genetic engineering and therefore quicker regulatory approval and acceptance would be expected.
- *Cloud-based bioinformatics(Crop2):* Cloud platforms to link genomic discoveries to plant breeding decisions, programme design and monitoring.
- *Short Stature Corn (Crop3):* Hybrid crop that grows shorter and therefore reduced loss from wind damage (lodging)
- *Drone seed spreaders (Crop4):* Mostly US based applications. Currently small niche but reduces compaction of soil.
- *infrared reflectance (NIR) (Crop5):* Non-invasive technique that measures the reflection of different wave light lengths to monitor the composition of grain as it ripens (moisture, starch, protein, and oil content)
- *Genetic profiling/Genomic testing in breeding programme (Crop6):*A form of marker assisted management (MAM). Genetic tests can give producers a better idea of how crops will perform in specific situations. These tests enable producers to sort crops into particular management groups.
- *Genetic profiling/Genomic testing in breeding programme (Crop7):* Marker-Assisted Backcrossing (MAB). The goal of backcrossing in commercial agriculture applications is to move a single trait of interest—such as drought tolerance, high productivity, or disease resistance—from a donor parent to progeny. This process significantly accelerates backcrossing programs and reduces the time to release of commercially viable plant lines.

Pest and disease management

- *Automated expert system for field crops (crop8):* Fusing IPM with Automated Decision Support Tools leads to early identification of pest/diseases. Current focus is on weed and pest detection.
- *Crop walk UAVs (crop9):* UAVs which monitor disease through infrared (same as NIR (Crop5) but applied to crop health using different algorithms.
- *Nano-TiO_2 Photo Semiconductors (crop10):* The nano-TiO2 applications of degrading pesticides, plant germination and growth, crop disease control, water purification, pesticide residue detection.

Targeted nutrient management

- *Nano fertilizers (crop11):*A nano-fertilizer refers to a product in nanometer regime that delivers nutrients to crops. It will improve nitrogen use efficiency.

- *Biological nitrification inhibitors (crop12):* BNI is the natural ability of certain plant species to release nitrification inhibitors from their roots that suppress nitrifier activity.

3.2.5. Buildings and Energy Management

Crop storage

- *Radio wave grain drying (B1):* Radio wave grain drying is an emerging technology that uses radio waves instead of heat to remove water from the inside out of individual grains. Reduces grain drying energy costs but also claims to improve grain quality by reducing over- and under-drying.
- *Real time monitoring of stored grain/potatoes (B2):* Linked robotic drones to check moisture content in grain stores and potatoes. Autonomously digs through grain store and offers real time monitoring against set levels. Also, turns over grain to support drying function.

Energy management

- *Smart buildings (B3):* Increased monitoring and regulation of heating/cooling/ventilation etc. with increased control through apps. Similar to smart homes concept only applied to sheds and stores. Applied to glasshouses/smaller kit could be developed for polytunnels.
- *Smart Cattle sheds(B4):* Monitoring system based on LoRa, a low-power, long-range wireless communication technology. The proposed system wirelessly collects real-time stable information from sensors installed in the cattle shed, and the collected data are analysed by the integrated management system, delivered to the user, and controlled by the application.
- *Greenhouse automation(B5):* Using sensors and connectivity reporting on greenhouse condition data, smart weather stations can also use predefined settings (and machine learning) to automatically adjust the environmental conditions to match the given parameters.

Capturing emissions from buildings

- *Thermal-catalytic oxidation(B6):* Catalyst-based oxidation by the passage of hot ambient air (approx. 400°C) over cheap catalysts like Hopcalite (Cu-Mn Oxides). Could run through animal sheds to capture methane.
- *Photocatalytic oxidation(B7):* Ultraviolet light is used to split an oxygen molecule into two free radicals. In photocatalytic reactors, a catalyst such as zinc oxide or titanium dioxide is used to increase the generation of free radicals, and thus the methane reaction rate. This is very attractive as ultraviolet light in sunlight can be used, for example on the roofs of cattle barns.
- *Zeolite or membrane extraction(B8):* Methane extraction by gas separation membranes is a potentially feasible method of methane removal through sheds. These methods rely on techniques that are already in widespread industrial use that could likely be readily upscaled in a way that a more experimental technology could not, which is a significant advantage when dealing with the immediate need for decarbonisation.

- *Replace farm buildings with sustainable materials(B9):* Concrete is a significant contributor to CO_2 replaced by sustainable wood products (e.g., hybrid sandwich wall (half concrete/half wood); or Hemp (with warming properties)

Tractors

- *Autonomous and semi-autonomous tractors (V1):* Self-driving, more accurate than human driver; much lighter and driven by electrical motors hence reduces soil compaction

Equipment

- *Autonomous sprayers(V2):* Combining robots and drones to direct spraying on grass (Autospray). John Deere autonomous spray system with adjustable heights for row cropping
- *Continuously variable transmission (V3):* Continuously variable transmission with an electro-mechanical power split- produces power which links up tractor to e.g., slurry sprayer - gives lighter load and more power, so less compaction and claims to be carbon neutral.

Fuel Management

- *Electrification (V4): E*lectrical drives to replace engines and hydraulics. Electric motors have huge torque at low speeds, they are more efficient, more reliable, and lighter.
- *Hydrogen powered vehicles (V5):* Currently mixes hydrogen with diesel as a hybrid engine - introduced recently in the Netherlands. Claim of reducing CO_2 by 40%
- *Methane powered vehicles (V10):* Methane powered production tractor. Use of biomethane (from animal or agricultural waste) which powers the tractor. Alternatively, there may be possibilities in the future for refilling directly from the gas grid network or at specific biomethane station.

Smart Monitoring

- *Soil and Water Sensors (V6):* Sensors allow examination of the soil's moisture and nitrogen level. Thus, farmers know which parts of their arable feed need watering or fertilizing.
- *Central command of vehicles and equipment (V7):* A central control booth with joystick control, display, and networking. Allows the farmer to control all vehicles with support from AI algorithms from a single point, e.g., integrating real-time weather data and syncing activities. This therefore provides a time and labour-saving solution.
- *Automated harvesting equipment (V8):* 3D imaging for automatic sorting in field to reduce waste. Seems to be tested on a traditional tractor set up but could be coupled to advanced equipment. Uses 3D laser scanners, robotics, image processing and deep learning software.
- *Machine Synchronisation(V9):* This technology supports the unloading of the combine on the trailer to avoid spilling of grain. Supports multiple machines in the field at the same time.

3.3. Short listing Approach

Once compiled and agreed by Scottish Government the long list was then assessed in terms a number of criteria. These are highlighted below.

- ***System Fit:*** how the technologies will fit the current farming system or would it require a change, e.g., more mixed farming; access to the power grid or nearby facilities to enable its application. Running from 1(fits now) to 5(requires a major system change). Full scale: 1=fits now; 2=requires a small change in the farm, 3= requires change in an enterprise, 4 =requires a change in more than one enterprise; 5=major system change.

- ***Level of technology readiness:*** the lead-in time and market rollout of a technology. This reflects the current state of the technology, i.e., has it been introduced elsewhere and needs to be modified or is it at the conceptual stage. Runs from 1(near market) to 5(not ready within 20yrs). Full scale: 1=near market,2=development stage, 3= applied research stage, 4= strategic research stage, 5= not ready within 20 yrs.

- **Cost of Implementing for the farm**: the amount of on-farm investment for implementing the technology to a cost-effective level. These include capital and running costs mostly but also training costs if it involves new equipment that is radically different. Runs from 1(no change) to 5(high level of investment). Full scale: 1=no change, 2=minimal cost, 3=small cost, 4= higher level of investment, 5= significant level of investment.

- ***Impact on the Market****:* This accounts for any productivity effects on adoption - e.g., would adoption lead to a loss in efficiency despite the GHG gains, but also brings in savings as well. Hence the scale reflects the level of market disruption that the technology would cause from either an increase or a decrease in prices. Running from 1:(no effect on price) to 5(high effect on price). Full scale: 1=no effect on market price, 2=small change in market price, 3=some change in market price, 4=higher level of change in market price, 5=significantly high level of change in market price.

- ***Level of market acceptance*****:** the level of acceptance of the approach within current supply chains. How will this fit the way the supply chain operates? Would it require modifying materials/methods/machinery etc. Runs from 1(feasible) to 5(not feasible). Full scale: 1= feasible within the current supply, 2= small effect on supply chain; 3=some effect on supply chain; 4=large effect on supply chain; 5= not feasible within the current supply chain.

- ***Social Acceptance***: the level of acceptance for both farming communities and society as a whole. Are there any production processes that would be seen as controversial for society as a whole. Full Scale: 1(total acceptance) to 5(no acceptance). 1= total acceptance, 2=few concerns; 3= some concerns; 4= major concerns; 5= no acceptance.

- **GHG Savings:** The expected impact on GHGs if the technology were adopted within Scotland level. This considers the current structure of Scottish farming and the potential for GHG savings. Full scale: 1(no impact) to 5(high impact). Full scale: 1=no impact, 2=low level impact, 3=medium impact, 4=moderately high impact, 5=high impact.

The technologies were ranked individually against these criteria by the 6 researchers. Each criteria is was weighted equally to give an implementation scale to reflect the consensus. This was then ranked in terms of the lowest score, which identifies the most feasible of the long list of technologies that could implemented.

Secondly, the GHG score was also ranked by the researchers in terms of the predicted GHG savings that each technology could offer. This was an estimate based on the potential population that the technology could be applicable to, e.g., all livestock, or specific species or systems. Then the average of the implementation ranking and the GHG ranking were used to estimate the final rank. This means that the GHG savings were equally ranked with the implementation score[7],[8].

3.4. An assessment of the performance of the candidate technologies

The candidate technologies were explored in-depth to provide a fuller description of the technology, the GHG saving potential, an estimation of the costs for adoption at the farm level, their applicability towards the sector and any interaction effects. These are detailed within the Appendix. A summary table (table 3) is provided below of the potential GHG saving and the uncertainties around these estimates.

Significant gaps emerge in some of the technologies through lack of a systematic evidence base or, more fundamentally, a paucity of trials which reflect Scottish conditions and contexts. In summary, the table indicates a significant GHG saving potential for most of the technologies at the most optimistic end, but a number have shown no effect given the context and applications.

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[7] Within the spreadsheet produced as part of this project there is the oppourtunity to change weights for the individual aspects of the implementation scores, if there is a desire to promote one aspect, e.g., cost saving, over others.
[8] The full ranking and scores are available in the spreadsheet produced as part of this project.

Measures Applicable to tillage and grassland`

Key	Main Farm Functions	Functional Area	GHG Saving	Uncertainty
L5	Land management	Rock dust	Abatement potential with agricultural soils in the UK has been estimated between 0.2 and 0.8 tonnes of CO_2 per tonne of basic rock	Low uncertainty: sequestration potential will vary depending on the chemical composition of the rock material. Ultrabasic rocks with especially high magnesium and calcium contents can sequester > 1 tonne of CO_2 per tonne of rock applied (Kantola, 2017). There is some evidence that rock minerals may also contribute to the reduction in methane and nitrous oxide emissions from soils, whilst boosting the productivity of arable soils (Blanc-Betes *et al.* 2021; Das *et al.* 2019).
L4	Land management	Biochar	UK studies estimate an abatement potential of 0.7-1.4 t CO_2eq/ oven dry tonne	Medium uncertainty: total GHG abatement will vary depending on organic feedstock, production technology, and predicted effects on crop yields.
L2	Land management	Underground Sensors	Unknown	High uncertainty: No study on underground sensors and GHG savings exist but a number promote the idea that this would have benefits. Savings would be on nutrient application, and reduced crop failure may have positive, if marginal, effects on CO_2 above ground sequestration.
Crop2	Crop Management and Production	Cloud-based bioinformatics	Unknown	High uncertainty: Would improve crop production and soil health through targeted solutions. Note benefits may be offset by the carbon emissions generated from large scale computing arrays.
Crop12	Crop Management and Production	Biological nitrification inhibitors	Tropical grasslands: reduce N_2O emissions in the field by up to 90%. New Zealand: reduce nitrous oxide emissions by 50% for the use of plantain within species rich swards.	High uncertainty: The mechanism of this effect is not entirely clear, as it could result from the direct effects of plant exudates on soil nitrification rates but could also result from digested forages having an impact on nitrification rates in the urine deposited by grazing livestock.

Measures Applicable to livestock

Key	Main Farm Functions	Functional Area	GHG Saving	Uncertainty
Liv10	Livestock Management and Production	Feed Supplements (Seaweed)	Beef -56% CH_4; Dairy -22% CH_4; -53% CH_4 Sheep	High uncertainty: Only several trials conducted within the US and Australia
Liv15	Livestock Management and Production	Feed Supplements	Several technologies show reductions in methane yield of 5-15%.	Medium uncertainty: reflecting differences between supplements and the amount of data available. Though there is a higher uncertainty concerning interactions between different supplements (e.g., will there be synergies or trade-offs).
Liv38	Livestock Management and Production	Microbial proteins	Unknown	High uncertainty: Considered as a replacement for soya-based meal and is therefore carbon off-setting. Though dependant on the mixtures of proteins with other feeds.
Liv1	Livestock Management and Production	Genetic profiling/Genomic testing in breeding programme	Genetic gain per generation would be equivalent to an up to 8% reduction in methane emissions per year / cumulatively up to 50% in 10 years.	Low uncertainty: Based on research conducted at SRUC Beef Research Centre and therefore reflective of Scottish conditions.
Liv44	Livestock Management and Production	Fluoride and tannin additive to manure	In pigs: 95% reduction in ammonia emissions, 99% reduction in methane emissions, and 50% reduction in odour (Dalby, 2020b).	High uncertainty: Studies at lower dosages have not identified any emission reductions (Dalby, 2021). In addition to direct emission reductions, tannic acid with fluoride(TA-NaF) will reduce nitrogen losses from manures, improving crop productivity and potentially reducing emissions related to synthetic fertiliser use.

Key	Main Farm Functions	Functional Area	GHG Saving	Uncertainty
Liv47	Livestock Management and Production	Methane Vaccine	Efficacy ranged from 7.7% to 69% methane reduction	High uncertainty: Multiple studies were unsuccessful *in vivo.*
B4	Buildings and Energy Management	Smart Cattle sheds	Estimate of around 14 to 25% reduction in to CO^2e for beef finishing	Medium uncertainty: Savings relate to the SRUC GreenShed project and therefore reflective of Scottish conditions. However, this is a single trial.
Liv37	Livestock Management and Production	Connected animal mounted sensors	Beef: Modelled scenarios for PLF introduction reduced both total farm emissions (2.4 - 7.4%) and emission intensities (1.5 - 11.9%); Dairy: showed reductions in whole farm emissions (0.4 - 0.9%) and all scenarios reduced emissions intensities (3.0 - 9.0%).	Low uncertainty: use of Agrecalc (a carbon foot printing tool based on Scottish conditions) to model impacts of PLF introduction on average Scottish beef and dairy farms.

3.5. Implementation pathways of candidate approaches

The previous section identified the GHG saving potential of these technologies. The purpose of this section is to examine the candidate technologies in terms of their current stage of development, barriers to market entry and the potential intervention approaches that could be used to engender faster uptake of these technologies. We classify our technologies against the following criteria:

- **Current stage of development:** These range from a theoretical proposition, a single trial, at the testing stage, near-market, niche/roll-out elsewhere.
- **Potential timescale:** An estimate of the time to market of these technologies, given the barriers and issues around the candidate technologies.
- **Potential barriers:** the main barriers that inhibit the further development of the technology, or which could be addressed to lead to more rapid entry to the market.
- **Intervention logic:** To understand the rationale for intervention, based on the characteristics of the technology and whether this is purely private enterprise, or whether the public sector has a role.
- **Type of intervention:** Given the barriers to the technology, what interventions are available which may lead to more rapid development. Most of this will be directed at the sectors developing the technology, e.g., the agrochemical sectors, but other interventions would be focused on the farm level, e.g. to generate demand and support behavioural change to make product development more desirable.
- **Farm Types:** The most likely farm types that would benefit from the product, to give an indication of the potential market size if adopted.

This will offer some insight into how near the candidate approaches are to market and help inform where interventions could be focused. Thus, we consider some of the implementation pathways for developing frameworks for support, regulatory baselines and stimulus for private sector investment. These are presented below.

*3.5.1. Seaweed (*Asparagopsis*)*

Intervention Logic: Feed Additives are mostly developed through the commercial sector. Some patents are held by public research institutes and university which implies some public good argument for intervention, mostly around mitigation of methane and in the ruminant sector this is a significant portion of overall GHGs.

Type of intervention(s) to enable technology: Main vehicles of support may be regulatory recognition, namely authorities could change the way seaweed as a methane mitigator is regulated in the EU (i.e., requiring approval as a zootechnical feed additive). Moreover, this is a non-native species and this would need a source of sustainable seaweed to avoid negative consequences.

Current stage of development	Potential timescale		Potential barriers		Farm Types Suitable
near-market	5-10 years	Patents jointly held by CSIRO and James Cook University, Australia. 'Future Feed pty' is a company established to licence this intellectual property for the development of supply chains of *Asparagopsis* for the feed industry. Authorities could change the way seaweed as a methane mitigator is regulated in the EU (i.e., requiring approval as a zootechnical feed additive). This would either prevent such products reaching the market or require several years for relevant dossiers to be compiled and reviewed.	Availability of seaweed; Lack of Infrastructure; Regulatory compliance on Iodine in foods	Limits on supply of safe feed may be a barrier to implementation. *Asparagopsis* can contain a high level of iodine and high levels are potentially toxic, and transfer into milk. Current EU (and UK) maximum concentrations of iodine in dairy and beef diets (5 and 10 mg/kg complete feedstuff, respectively) may limit the use of *Asparagopsis* as a feed material. Implementation may also be constrained by production capacity (wild harvesting, at sea cultivation or tank-based cultivation on land).	Beef; Dairy; Sheep; Pigs; Poultry

3.5.2. Feed Supplements (as methane mitigators)

Intervention Logic: Feed supplements targeting methane address one of the major externalities in Scottish livestock production. Many feed supplements have been evaluated as methane mitigators but few have found practical application.

Type of intervention(s) to enable technology: Incentives (market or regulatory) are needed to drive use of supplements that reduce methane but which do not deliver improved animal performance that farmers can currently monetise, e.g. increased efficiency. Different additives, working via different mechanisms, may be complementary hence interventions may be needed to encourage collaboration between suppliers of different supplements (who otherwise behave as competitors).

Current stage of development	Potential timescale		Potential barriers		Farm Types Suitable
near-market	1-15 years	Feed supplements can be simply but usefully classified by mode of action: 1. Direct inhibitors of methanogenesis, 2. Alternative hydrogen sinks, 3. Suppressors of hydrogen formation (fermentation). Each class contains supplements close to market (e.g., 3-NOP, nitrate), supplements that have been extensively researched but not applied, for various reasons (e.g., statins, monensin, saponins) and novel approaches currently undergoing varying degrees of active research (e.g., plant extract screening programmes, probiotics). Thus, the potential timescale for development and implementation is large.	Many potential obstacles between initial discovery and practical adoption. Even when these are overcome, adoption will require incentives (financial or regulatory).	There may be insufficient proof of efficacy, lack of data on interactions between supplements and the environment in which they will be used; lack of vested interest to fund product development (e.g., lack of IP ownership); lack of viable supply chain; practical challenge of reaching target animals (e.g., extensive grazing systems); challenges in the regulatory pathway; lack of financial reward to end-users and/or supplement manufacturers.	Beef; Dairy; Sheep

3.5.3. Rock dust

Intervention Logic: Rock dust is commercially available and applied by a small number of niche farmers. Main issue is measuring GHG potential and wider environmental impacts on food production through transfer of heavy metals.

Type of intervention(s) to enable technology: This limited evidence base requires further testing to prove efficacy to other farmers but also to identify the key sources of rock dust which minimise exposure to potentially toxic elements.

Current stage of development	Potential timescales (years to market)		Potential barriers		Farm Types
at the testing stage	3 years	There is already application of rock dust to agricultural soils small-scale in tropical climates. More widespread use depends upon rigorous testing and analysis of the greenhouse gas mitigation potential, alongside work to ensure that the technology can be applied without any adverse environmental safety consequences.	Cost of product; Regulatory Compliance	The availability of rock dust varies across the country, and transport costs can be high. There are also concerns that some materials may contain heavy metals for potentially toxic elements that would preclude their use from agricultural soils.	Cereals; General Cropping; Horticulture

3.5.4. Biochar

Intervention Logic: Biochar is commercially available (e.g., SoilFixer; Pyreg) but there are limited production facilities and competition for reliable organic inputs for production.

Type of intervention(s) to enable technology: High Capital costs could be reduced through targeted supported for business. More support for testing of spreading equipment; improved clarity on the role of biochar and waste management licensing.

Current stage of development	Potential timescales (years to market)		Potential barriers		Farm Types
niche/roll-out elsewhere	1-5 years	Biochar is a mature technology; it is already produced across the world for diverse uses. A recent report estimated the time to implementation for biochar in Scotland at 1-5+ years (Hazeldine, 2019). Notably, a longer time frame and higher costs will be required to link biochar production with bioenergy and carbon capture and storage, though this would achieve higher greenhouse gas abatement in the long term.	Availability of feed stock; Regulatory; Efficacy; Capital Costs	One of the largest barriers to implementation of biochar as a mitigation technology is uncertainty in the longevity of soil carbon storage. At the farm level, further barriers include logistic challenges in spreading low density material on large areas of farmland, unclear impacts on crop productivity, and high costs. At the production level, barriers include high capital costs for new production facilities, competition for organic feedstocks with other technologies, and a lack of clarity in waste management licensing for Biochar (Shackley & Sohi, 2010).	Cereals; General Cropping; Horticulture

3.5.5. Microbial Proteins

Intervention Logic: Commercially developed products exist but focus has been on high value sectors, e.g., poultry, pigs, fish. There is little work in cattle or sheep sectors.

Type of intervention(s) to enable technology: Regulatory or tax related interventions could be considered, e.g., for replacing soya-based meal, may encourage innovation and adoption to overcome technical barriers.

Current stage of development	Potential timescales (years to market)		Potential barriers		Farm Types
near-market	3-5 years	Profloc and Feedkind Terra are examples of commercial products though focused in the US or the fish/poultry/pig sector	Technical Barriers	The small number of studies may reflect a decreasing marginal effect, e.g. when replacing soya based meal with single cell proteins (Hombegowda et al 2021). A technical barrier also exists when scaling up the technology, e.g., where the process of photosynthesis is used by these organisms to capture CO_2 from the air as a carbon source, ensuring enough light reaches all algal cells as their density increases over time requires innovative tank design and/or lighting systems.	Poultry, pigs, cattle, sheep

3.5.6. Underground soil sensors

Intervention Logic: Commercially developed but the main factor is the high cost of equipment plus training for their optimal usage. This has a diffuse path to GHG saving - through the saving of input resources - which makes it attractive from a private productivity perspective. Though there are concerns around tying farmers into long term contracts for analysis. This may argue for some public intervention to support translation of metrics from the sensors.

Type of intervention(s) to enable technology: Lower cost alternatives could be offered through development and support for innovation. Additionally training of farmers - in metrics and their use - may encourage more adoption. Public grants for developing open-source platforms for analysing data would also address the issues around tying farmers into lengthy contracts.

Current stage of development	Potential timescales (years to market)		Potential barriers		Farm Types
near-market	1 to 5 years	Already available from suppliers but no evidence of uptake beyond trial farms outside of Scotland. No testing so would expect innovation leaders to try the technology. May need support to translate this to in-field operations in cereals, general cropping, and intensive grassland.	High capital cost seems main constraint	A product is commercially available and used in sports turf management. The cost of product seems to be the most prohibitive factor and may only apply to high value crops to ensure a return. The kit is sold with infrastructure support, e.g., echo station to boosts signals across the farm. Distance between underground sensors may be an issue in terms of connectivity and the topography of Scottish fields. No compliance or regulatory issues	General Cropping; Horticulture

3.5.7. Cloud based bioinformatics

Intervention Logic: Some initiatives are developing out of public-private sector initiatives. There is a potential link with the UK funded Agri-metrics innovation centre.

Type of intervention(s) to enable technology: Encouragement of skills and training for software and data analysts in metrics and offering training/degrees with an application in agricultural data and decision-making may support development.

Current stage of development	Potential timescales (years to market)	Potential barriers			Farm Types
near-market	1-5 years	Would only expect mid-to long term level of adoption if tech start-ups focus on Scottish agriculture.	Lack of Infrastructure	Main barrier seems to be lack of infrastructure, namely tailoring services to regional aspects of Scotland would require testing and trailing.	Cereals, Horticulture, General Cropping

3.5.8. Biological nitrification inhibitors

Intervention Logic: Key issue seems to be testing to generate robust evidence of impact. This technology has potential for high savings in GHGs but is relatively untested. Accordingly, there may be justification to support testing, development and trialling to monitor impacts within publicly funded research programmes.

Type of intervention(s) to enable technology: Through public funded research to trial and measure impacts in field conditions in Scotland.

Current stage of development	Potential timescales (years to market)		Potential barriers		Farm Types
a single trial	5-10 years	Given the need to generate new evidence, it would be anticipated that the time taken to implement BNIs would be between 5 to 10 years. The anticipated lack of any negative impacts would accelerate potential uptake of this technology, given probable ancillary benefits.	Lack of Evidence; Recognition in climate inventory	The major barrier to implementation would be the lack of evidence supporting the efficacy of BNIs. Following a demonstration of the nitrous oxide production mitigation potential in field-based experimentation it would be necessary to implement appropriate representation of this mitigation option in climate inventory reporting for it to be recognised as a mitigation option.	Cereals, Horticulture, General Cropping

3.5.9. Genetic profiling/Genomic testing in breeding programme

Intervention Logic: Public-Private work is ongoing towards this. There are private gains in high value sectors, in lower value sectors there may be less intent to support the technology.

Type of intervention(s) to enable technology. A key factor is the collection of enough data for testing. Hence testing stations, or something similar to the Beef Efficiency scheme, could support generation of more samples and data for increasing accuracy**.**

Current stage of development	Potential timescales	Potential barriers			Farm Types
niche/roll-out elsewhere	5-10 years	It is expected that microbiome-driven breeding is implemented by some breeding organisation within the next 5 year.	Lack of Infrastructure; Costs of sampling and storage	The present barrier for implementation of microbiome-driven breeding is mainly the logistics, as well as additional costs, involved in taking rumen samples, its storage and analysis to determine the rumen microbiome composition.	Cattle; Sheep.

3.5.10 Fluoride and tannin additive to manure

Intervention Logic: Currently developed through public R&D funding in Denmark. Intention would be to commercialise this through public-private sector networks.

Type of intervention(s) to enable technology: Seems to be lack of testing outside Denmark, so it would need support for demonstration within the Scottish context. Sourcing low cost tannins is also an issue from the supply chain which may lead to higher price of final product.

Current stage of development	Potential timescales	Potential barriers			Farm Types
single trial	10-15 years	Development is currently centred in Denmark at Aarhus University and the University of Southern Denmark through government funded research. The researchers intend to develop a granulate which can be marketed to farmers, but timelines are unclear as further trials are needed.	Cost of Product: Regulatory; Low evidence base	Major barriers include the lack of marketed or patented products, lack of effective dosage information, and the small evidence base which relies heavily on a small number of experiments in Denmark (Dalby, 2021). High costs of tannic acid and regulatory processes will provide an additional barrier to adoption as the technology matures.	Cattle

3.5.11. Methane Vaccine

Intervention Logic: Developed through Fonterra - a levy funded research body in New Zealand and this may argue for public-private sector initiatives, e.g. through levy boards, to develop these technologies.

Type of intervention(s) to enable technology: Requires testing but also focus on breeds and efficacy to reflect Scottish conditions. Testing and trials could be set up after regulatory approvals to confirm efficacy.

Current stage of development	Potential timescales		Potential barriers		Farm Types
a single trial	10 years	Still in development stage – estimated to be commercially available in 7-10 years after prototype (Reisinger *et al.* 2021)	Low confidence in results; regulatory and compliance related	Product still in testing but has quite variable results. If successfully passed trial, then regulatory compliance and testing would be expected.	Cattle; Sheep

3.5.12. Smart Cattle Sheds

Intervention Logic: All work on this has emerged from the public research institutes who are experimenting with agricultural design challenges. However, components of the shed, namely air filters, monitors etc. would seem to be the province of the private sector. Also, the payback, in terms of energy saved and associated productivity, may support more private investments.

Type of intervention(s) to enable technology: This would equate to improving or, more likely, replacing a farm building. There is a history of support for capital payments, e.g., for buildings and drainage in the 1980s. However, the cost of establishing smart cattle sheds would be prohibitively expensive for the Government.

Current stage of development	Potential timescales (years to market)	Notes	Potential barriers	Notes	Farm Types
at the testing stage	5-10 years	Still at trial stage, early versions retrofitting sheds may be in next 5 years.	Cost of Product; Lack of Infrastructure	Cost of the product will be high, also a lack of infrastructure in terms requirements for building, materials, networking and servicing.	Housed, e.g. finishing cattle

3.5.13. Connected animal mounted sensors

Intervention Logic: Mostly the domain of the private sector both in the development of sensors but also the software to monitor the output of these sensors. However, public-private partnerships to support testing and trailing these as a system has occurred. Note though, this may require locking in farmers into contracts for analysis services.

Type of intervention(s) to enable technology: The type of technology is available, but the costs of the product is prohibitive. Nevertheless, companies argue that a payoff over time will occur, hence training farmers and providing support for investment decision making may be a route to support uptake. A further constraint is patchy rural broadband for transfer and relay of data in real time. The general progression of improving rural broadband from the Scottish Government may overcome this barrier.

Current stage of development	Potential timescales (years to market)	Notes	Potential barriers	Notes	Farm Types
niche/roll-out elsewhere	On market	Many systems are already available for commercial use; however, it should be noted that these commercial systems are often not validated for their intended use they are marketed for.	Cost of product; Lack of infrastructure - rural broadband.	Recent work found the cost of systems was identified as the main barrier to uptake (Bowen, forthcoming); however, this is likely to be coupled with lack of understanding on return of investment. Other limitations/barriers included internet connectivity requirements in regions often lacking in access to sufficient coverage, and not understanding the benefits of the system or how to fully use the system. These limitations and barriers are also applicable to dairying systems.	Cattle; Sheep.

4.0 Conclusions

4.1. General Summary

We identified a range of technologies and a schema for understanding where new technologies could impact farm level production in Scotland. This yielded 86 viable technological routes that have not previously been considered in-depth by previous studies. Through a series of scoring criteria, and interest from Scottish Government, we explored 13 candidate technologies for further inquiry.

All of these candidate technologies reveal high levels of uncertainties around both the potential GHG saving and the cost and benefits of implementation at a farm level. This includes the range of feed additives and supplements, but also ways in which soil carbon can be improved and how crops and animals will be monitored to reduce productivity losses from health and welfare issues. Only a small number have been tested within a Scottish context, so further development, trialling, and proof of concept type studies are needed to understand whether they have value for future interventions.

4.2. Recommendations on key technologies

All these technologies provide some potential for application in Scottish agriculture. Those, within the short list, that could be prioritised for more Scottish Government effort would, we argue, be:

- **Feed additives.** These are easily implemented on-farm compared to other technologies and target enteric methane production, the most significant greenhouse gas from Scottish agricultural production (Thomson and Moxey, 2021). There is a dynamic feed sector operating globally with a focus on methane reduction. However given the diversity of feed additives, the application of feeds to Scottish contexts lacks evidence in terms of their efficacy and the potential trade-offs between GHGs and productivity. Whilst development, testing and trialling can be part of Government intervention a key issue is the need for regulatory approval to ensure these additives are safe for human and animal consumption. This is the role of the private sector and those additives declared safe can be tested for Scottish contexts. Exploring the relationship between combinations of feed additives would offer some value in understanding the effects and how these may improve or negate the methane reducing effect.
- **Rock dust.** This product seems to show potential for reducing nitrous oxide emissions across arable land. Moreover, this is near market and may be supported through trialling. Additionally, the input stock for rock dust could be generated from waste from the construction industry. However, issues around application rates and type of rock dust, in terms of identifying potentially harmful toxic effects would need to be resolved through a series of applied testing within the Scottish context.
- **Microbial Proteins.** This represents a product with a wide set of production techniques, e.g. from algae or fermentation tanks. The attraction of these proteins would be as an alternative to imported soya meal, which constitutes a large part of

livestock diets. Microbial proteins are currently rolled out to high value sectors, e.g., aquaculture, with little work on cattle and sheep systems. There are technical barriers to scaling up production, hence further investment into development of ways to produce these proteins could be a way to overcome these scaling issues.

- **Animal mounted sensors.** This focuses effort on the main livestock production sectors and effectively targets animal health, which is a significant intervention identified in the MACC (Eory et al., 2021). Whilst the production and supply of sensors is supported through commercial development, there are high costs to adoption, as well as the need for training and demonstration to operate these systems at their optimal levels. Hence, support for capital investment may be justified, both for supporting investment but also for establishing best practice in operating sensors.

4.3. Further Issues to Consider

The effect of disruption is making newer, more costly technologies more attractive

At time of writing, recent disruptions in the supply of materials - but also the longer-term impact of climate change on security of imports - have led to a rise in cost of inputs. This will change the rubric of these technologies in terms of their cost-effectiveness, but also in establishing the rationale for investment in technologies which can save inputs and ensure consistent supply of outputs. This makes these and other technologies candidates for accelerated further development, for instance the development of single-cell proteins for the replacement of imported feed, but also those which were not explored on the short list. A prime example of this is 'on-farm fertiliser production from manure with plasma technology'. Whilst considered too costly to implement it offers replacement of a vital input - ammonium-nitrate - in the production of manure.

We should consider both public and private intervention pathways

The technologies tend to differ in terms of whether they are wholly privately funded initiatives, or combinations of public-private funding and, in the case of large capital projects like smart cattle sheds, wholly within the scope of publicly funded research and development. Hence it is dependent on the technology and there are limits to how much the Government should or could intervene to both shorten the time to market of promising technologies but also encourage development of other technologies identified here that haven't met the criteria for the short list.

Encouragement of more demonstration and trialling

Encouragement of more trialling may be a means to increase adoption and provide evidence or otherwise of a technology's efficacy in the Scottish context. This is not wholly within the purview of the Scottish Government but other agencies, such as the Scottish Organic Producers Association have small trial projects on rock dust for example, and SRUC's research farm in Barony will apply plasma technology for on-farm fertiliser production.

Support and reward innovation within farming

In addition, Scotland, like all agricultural systems, is characterised by pockets of innovative farmers willing to experiment and develop discoveries on their own land. These could be utilised and encouraged to develop an evidence base on these technologies and, through peer-learning, provide a means to shorten the adoption time within the industry.

Encourage diverse skill sets within farming

Alongside trialling oppourtunities, technologies could be supported through the encouragement of skills sets not currently associated with agricultural production. This will allow application to farming problems, such as AI and nanotechnology, but also delivery of open-source analysis packages and training for farmers to encourage long term investment and understanding of multiple metrics to inform decisions. One aim of the new EU CAP is generational renewal and, if Scotland's replacement policy follows, then a new generation could bring those wider skill bases to the industry.

High uncertainties tend to typify these new technologies

Most of the technologies presented suffer from a lack of a systematic evidence base in which to firmly pronounce their usefulness to Scottish agriculture. Whilst there is a large literature on feed additives, the diversity of what constitutes an additive has led to a lack of application in contexts relevant to Scotland. Hence, those feed additives identified through this short list should be further trialled to understand the efficacy of their impact.

Addressing regulatory and legal barriers

A further barrier is the regulatory and compliance pathways. These are necessary and relate to how technologies are classified, e.g. especially in the case of feed additives and alternative proteins may influence how these technologies may shorten their journey to market. A number of additives which provide potential in reducing methane are also required to undergo regulatory testing. It is unclear how, in a post-EU Scotland which is seeking trade deals with other countries that will have different rules and regulations, whether this will accelerate promotion and adoption of candidate technologies previously limited by EU regulations.

4.3. Suggestions for further work

We have supplied, as part of this project, a long list of technologies as a queryable spreadsheet. This should be seen as a dynamic list, for the addition of other technologies. Notably, for most of the technologies there is a minimal applied literature, and we would expect a more robust evidence base to develop around these technologies over time.

Whilst we believe we have explored the key evidence and identified the main technologies and technology areas; the list of measures should be used to create a dialogue with other groups around how we can develop the list further and identify oppourtunities for including 'grey' or undisclosed research findings.

Finally, whilst a number of the technologies are currently considered unfeasible, the cost-effectiveness of these technologies will change as the costs of inputs change, or mechanisms for agricultural policy comes into focus. Ideally, these technologies will form part of an updated MACC to understand the cost-effectiveness for investment and assure business of the value of further investment for development. This is currently hampered by uncertainty around estimates on the GHG, productivity and economic costs for implementation.

Appendix 1: Detailed Analysis of Candidate Technologies

***A1. Seaweed (*Asparagopsis)**
***Functional Group:* Livestock Management and Production**
Sub-Functional Group: Feed Management; Feed Supplements

Overview

Seaweed is a term for a diverse range of marine microalgae. Seaweeds are phylogenetically classed as *Rhodophyta*, *Phaeophyta,* or *Chlorophyta*, but are more commonly referred to as red, brown or green seaweed, respectively. Some seaweed species (particularly red species) contain halogenated methane analogues, such as bromoform ($CHBr_3$), which inhibit methane production by reacting with vitamin B12, suppressing the cobamide-dependent enzyme methyl-coenzyme (CoM) reductase step in methanogenesis. The species exhibiting the highest potential for enteric methane reduction is the red species *Asparagopsis taxiformis*.

GHG saving potential

There have been a small number of trials testing the efficacy of *Asparagopsis* for enteric methane reduction in live animals (*in vivo*) (beef:2, dairy:2, sheep:1). Seaweeds fed in these studies were harvested in Keppel Bay, Australia, or in the Azores, Portugal. Baseline diet and feeding duration varies widely between studies. There have been a wider range of laboratory (*in vitro*) studies (n=13). The *in vitro* studies investigate a wide range of seaweeds (red: 12, green: n=5; brown: n=5; mixed: 1) harvested from a variety of locations including Australia, Portugal, Korea, the USA and Canada.

All identified *in vivo* studies reported a significant reduction in methane yield for at least one dosage level. The average observed reduction in enteric methane emissions from beef cattle was 56.0 ± 9.4%, for dairy cattle 22.2 ± 9.75%, and for sheep 53.0 ± 13.78%. However, due to the small number of *in vivo* studies, these reductions are associated with wide 95% confidence intervals (beef: 37.6 to 74.3%; dairy 3.1 to 41.3%; sheep 26.0 to 80.0%). Mean inclusion rates of seaweed in these studies were 0.59 ± 0.19% feed organic matter (OM), ranging from 0.05 to 3% OM, with significant reductions in methane yield found at dosages as low as 0.1% OM in dairy cows (Roque et al., 2019) and beef cattle (Kinley et al., 2020).

The *in vitro* studies found an average methane reduction of 55.0± 7.3% for red species, 16.0 ± 5.2% for brown species and 34.6 ± 5.9% for green species. In studies where *A.taxiformis* was used, mean methane reductions of 74.0± 11.1% were achieved and where inclusion rates were≥2% OM, reductions in methane were consistently greater than 95%.

The below table summarises enteric methane reductions reported through *in vivo* studies. OM – organic matter; DMI – dry matter intake.

Abatement	Value	Country	Reference
Sheep			
0.5 to 3% feed OM	-15.3% to -80.7% CH_4 yield (g/kg DMI)	Australia	Li et al., 2018
Beef			
0.25 / 0.5 % feed OM	-69.7% / -79.8% CH_4 yield (g/kg DMI)	USA	Roque et al., 2021
0.05 / 0.1 / 0.2 % feed OM	-9% / -38% / -98% CH_4 yield (g/kg DMI)	Australia	Kinley et al., 2020
Dairy			
0.1 % feed OM	-42.7% CH_4 yield (g/kg DMI)	USA	Roque et al., 2019
0.25 / 0.5 % feed OM	+3.6% / -29.4% CH_4 yield (g/kg DMI)	USA	Stefanoni et al. 2021

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	-	The effect will be greatest with *Asparagopsis taxiformis*
Manure CH_4		
Manure N_2O		
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions	Uncertain	Emissions associated with pre-farm production are uncertain but likely to be relatively small
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions	Uncertain	A study in Australia saw an uplift in productivity in red seaweed(Kinley et al., 2020)
Confidence in mitigation effect		
Cost-effectiveness**		
Confidence in cost-effectiveness		

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect

** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

Not known. Kinley et al (2020[9]) Found that the uplift in productivity would lead to cost savings. A study in Wisconsin of Red Seaweed on beef steers found a reduction in feed costs in finishing cattle with no effect on meat quality[10].

Applicability

Seaweed products used in efficacy experiments are simple preparations (dried and ground seaweed meal) that could be used directly on farm or incorporated into a range of feed products including pelleted compound feeds and potentially in feed blocks, tubs or licks as a means of reaching grazing livestock.

Interaction effects

Seaweeds are nutrient rich foods, including iodine and heavy metals, e.g., arsenic, mercury, lead, aluminium, cadmium, rubidium, silicon, strontium and tin (Moraiset al., 2020). Although these micronutrients are generally not at levels high enough to cause toxicity, bioaccumulation of arsenic, lead (Moraiset al., 2020) and iodine (Makkaret al., 2016)can occur and this level will vary dependent on the type, species and environmental conditions the seaweed was produced under (Roledaet al., 2018).Publications have concentrated on transfer of iodine from the animal to products for human consumption (particularly milk, e.g. Antayaet et al., 2019). However, high levels of iodine consumption by the animal can cause toxicity, leading to nasal and lacrimal discharge, coughing, pneumonia and skin irritation (Hillman and Curtis, 1979).More research into the conditions leading to high levels of trace nutrients is needed and great care must be taken that levels of minerals and heavy metals in the total ration do not exceed permitted or recommended levels.

A recent publication from The Netherlands (Muizelaar et al., 2021) has questioned the safety of bromoform for the animal. They examined the organs of two dairy cows slaughtered after receiving 67g of *A. taxiformis* per day for 22 days and found inflammation of the rumen wall and loss of papillae. They also detected Bromoform in milk, but this was not consistently across the experimental period.

Short-lived biogenic bromine-containing compounds, such as bromoform and bromochloromethane, emitted from seaweeds can cause ozone depletion (Wisher et al., 2014). The loss of ozone in the atmosphere leads to an increase in UVB rays reaching the Earth's surface which is harmful to human, animal and plant health. Increased farming of seaweed, particularly red species rich in bromine-containing compounds such as *A. taxiformis*, could lead to increased emissions of bromocarbons. Estimates ranging from a 6 to 11 times increases in bromocarbon emissions from Malaysian red seaweed farms have been projected with increasing production (Leedham et al., 2013). However, a paper currently in review concludes that *Asparagopsis* farming in Australia, at a scale sufficient to

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[9] Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed

[10] Seaweed can reduce methane emissions & feed costs in cattle. Report from University of California, Davis.

provide supplement for 50% of Australian cattle, would have an insignificant effect on atmospheric ozone (Jia et al., 2021). More research is required to gain consensus.

Bromoform (the main active methane-mitigating molecule in *Asparagopsis*) has been linked to hepatic and renal toxicity in rodents: data in ruminants appear lacking (see Muizelaar et al., 2021). The concentration of this compound in livestock diets is not currently regulated.

A2. Other Feed Supplements

***Functional Group*: Livestock Management and Production:**

Sub-Functional Group: Feed Management; Feed Supplements

Overview

The following feed supplements are close to or on the market and are not considered further in this review:

Product name	Active principle	Supplier	Regulatory category	Regulatory status
Bovaer 10	3-nitrooxypropanol	DSM Nutritional Solutions, CH	Feed Additive	Authorised for lactating ruminants (EU) Not yet authorised in UK
SilvAir	Nitrate	Cargill Animal Nutrition, USA	Feed Material	Nitrate is permitted as a source of NPN and Ca
Mootral	Garlic	Mootral, CH/UK	Feed Material	Garlic is a permitted feed material
Agolin Ruminant	Plant extracts (essential oils)	Agolin, CH	Feed Additive	Not authorised (under review by EFSA)
RumiTech	Plant extracts (essential oils)	Harbro, UK	Feed Additive	Authorised as sensory Feed Additive, not authorised as zootechnical Feed Additive (to reduce methane emissions)

A wide variety of feed supplements have been evaluated for effects on methane, over several years. For clarity, they are grouped here by mode of action. In summarising their efficacy, we have drawn mainly on the recent reviews of Arndt et al. (2021, an output from the Feed and Nutrition Network of the Global Research Alliance on Agricultural Greenhouse Gases) and Honan et al. (2021).

Direct inhibitors of methanogenesis

Halogenated compounds

Asparagopsis seaweed may prove to be a practical delivery mechanism for the halogenated compound bromoform, as discussed in a previous section.

Other halogenated compounds including bromochloromethane (BCM), bromoethanesulphonate (BES) and chloroform (the subject of research since the mid-60s) all inhibit the last step in the methanogenesis pathway. However, in contrast to 3-NOP, which specifically inhibits the enzyme, methyl-CoM reductase, these halogenated compounds inhibit the supply of methyl-coenzyme M. Early research reported marked reductions in methane production, but also rapid adaptation so that these reductions did not persist. Tomkins et al. (2009) encapsulated BCM (which is volatile) in cyclodextrin and were able to lower methane production in feedlot steers by 50-60% for at least 90 days. However, BCM has an ozone depleting effect and its use is restricted, leading Tomkins et al. (2009) to doubt that it would ever be commercialised as a methane mitigator. With the current focus on seaweed as a source of bromoform, it is hard to see potential in direct use of synthetic halogenated compounds as methane mitigators.

Statins

It has been known for several years that statins (e.g., lovastatin, mevastatin) inhibit the enzyme HMG-CoA reductase that is rate-limiting to the biosynthesis of a key component of the methanogen cell membrane (interestingly, this same pathway is involved in cholesterol synthesis, explaining the medicinal use of statins to prevent hypercholesterolaemia). Abrego-Gacia et al. (2021) reviewed six *in vivo* studies in which statins reduced methane yield by an average of 19%. Statins came from various sources, which may explain the wide variation in response in methane yield (from +3% to –42%).

Use of the same high purity statin preparations used in human medicine as feed supplements is probably unaffordable. However, statins are produced by various fungal species which can be grown quite simply on agricultural residues through solid-state fermentation. While this may offer a route to low-cost, home-produced supplements (especially suitable for use in developing countries), it may also be a disincentive to the development of supply chains of commercial supplements, especially as prior art (dating back to at least the publication of Miller and Wolin, 2001) is an obstacle to the protection of intellectual property (patent and commercial applications exist for the use of statins to suppress enteric methane in humans, and in environmental bioremediation).

The production of statin-rich fermentation products under controlled industrial conditions, offering appropriate quality control, has not, to our knowledge, been explored.

Nitrocompounds

Research, primarily in the US, has investigated effects of various nitrocompounds, including nitroethane (synthetic), 3-nitro-1-propionate and 3-nitro-1-propanol (naturally occurring) (Latham et al., 2016). The mode of action may be a mix of electron acceptor (like nitrate) and direct inhibitor, although the mode of action remains unclear. Research on these nitrocompounds, and the possibility of identifying naturally-occurring plant extracts enriched with them, is continuing (e.g., Bozic et al., 2022). However, with the focus on commercialisation of 3-NOP and nitrate, it seems unlikely that direct inhibition of methane by these other nitrocompounds will be developed into commercial practice.

Alternative sinks for hydrogen

Sulphate

Like nitrate, reduction of sulphate is thermodynamically favourable and will remove hydrogen from the rumen. Like nitrate, the amount of sulphate that can be added before issues of toxicity arise is limited, placing a ceiling on the amount of methane that can be prevented. Toxicity is due to the end product of sulphate reduction, hydrogen sulphide, which is inhaled after eructation from the rumen, leading to the condition polioencephalomalacia. Novel nitrate oxidising sulphide reducing bacteria, with the potential to minimise ruminal accumulation of both nitrite and hydrogen sulphide (both undesirable), have been identified, but little seems to have been done to develop them as viable probiotics for the purpose of methane mitigation.

Distillers' grains contain a higher level of sulphate than other concentrate ingredients. One opportunity to use sulphate to deliver a small but real reduction in methane is to recognise its contribution when formulating concentrate feeds using distillers' grains.

Organic acid salts (fumarate, malate, succinate).

The reduction of fumarate, malate and succinate to propionate consumes hydrogen that would otherwise be used to make methane. There would be no major regulatory or practical barriers to the use of these salts as feed supplements, if found to be effective. Despite evidence of efficacy *in vitro* (reductions in methane yield of around 10%), responses in vivo have been generally small, leading Arndt et al. (2021) to classify fumarate as ineffective.

Further work is needed to explore interactions between these salts (as hydrogen sinks) and other strategies (e.g., use of direct methane inhibitors). One idea to improve the efficacy of fumarate is to add a probiotic microorganism to accelerate its reduction to propionate. One might then foresee a three-way combination: a methane inhibitor, fumarate as an alternative hydrogen sink, and a probiotic to promote the metabolism of fumarate. Combining different approaches in this way, even if technically successful, would add significant cost, and each element would require regulatory approval.

Biochar

It has been proposed that biochar, with its very large surface area, may itself act as an alternative electron sink, and one recent paper reported a 10% reduction in methane in growing steers (see Honan et al. (2021) for reference and discussion). However, biochar may affect emissions through other mechanisms, so responses may be variable and unpredictable. Further research is certainly justified.

Reductive acetogenesis

The reduction of CO2 by H2 to form acetate is an alternative to its reduction to form methane, and reductive acetogenesis dominates over methanogenesis in the guts of, for example, termites and marsupial mammals. However, at hydrogen concentrations typical of the rumen, methanogenesis is thermodynamically more favourable than reductive acetogenesis. Addition, as probiotics, of bacteria capable of reductive acetogenesis has not, hitherto, successfully lowered methane emissions *in vivo*.

It recently been shown that ruminal concentrations of hydrogen rise after feeding, with a lag before a rise in methane production. Hydrogen levels also rise when methane is inhibited directly, for example by 3-NOP. Is it possible that strains of reductive acetogens can be found that make a positive contribution, perhaps only for short period of the daily feeding cycle, in combination with other approaches to methane mitigation. There is at least evidence of continued research in this area.

Lower hydrogen production

Ionophores

Monensin is the best known and most researched ionophore antibiotic. These are naturally occurring, lipid soluble substances which are products of microbial fermentation (originally isolated from soil microorganisms). Monensin acts to change the end products of fermentation, favouring the production of propionate and thus generating less hydrogen.

There have been ~25 *in vivo* studies (dairy: 10; beef: 8; buffalo: 3; goat: 3; sheep: 1). Studies used a variety of forages for periods lasting from 5 to 200 days, and production response was measured in 18 of these studies. A total of 29 i*n vitro* studies were also identified. Across *in vivo* studies, a mean reduction in methane yield of 6.7 ± 1.6% was observed (dairy: 5.9 ± 2.5%; beef: 5.1 ± 3.5%; buffalo: 8.5 ± 1.5%; goat: 4.4 ± 2.5%; sheep: 11.0 ± 6.8%) with significant reductions found for at least one experimental condition in 13 studies. One study measuring methane emissions from beef steers over a ten-week period (using the SF_6 method) found a depression in emissions for 3-5 weeks, but the effect was transient (Guan et al., 2006). Significant differences in methane emissions have been found between treatment and control animals after extended periods of time in dairy cows (180 days, Odongo et al., 2007) and beef cattle (161 days, Hemphill et al., 2017). *In vitro* studies found mean reductions in enteric methane of 29.2 ± 3.1% with significant reductions observed for at least one dosage level in 22 studies.

Monensin was previously authorised in the EU as a feed additive to improve growth and feed efficiency in cattle, except lactating cows. This use in cattle was prohibited from January 2006. A preparation (bolus with controlled rumen release) was authorised as veterinary medicine for the prevention of ketosis in cows. This product is recommended to be dosed 3-4 weeks before calving and is expected to deliver monensin into the rumen for 95d. The contribution of methane mitigated during this time to the carbon footprint of milk production is not currently recognised.

Defaunation

Hydrogen-producing protozoa live in symbiosis with methanogenic archaea, and it has long been recognised that a reduction in the protozoal population (partial defaunation) is associated with lower methane emissions, partly by removing their associated methanogens and partly by reducing hydrogen production.

A variety of approaches to defaunation have been researched and are mentioned briefly below. None has yet found specific application for the purpose of methane mitigation.

Saponins. Supply chains of saponins (mainly from Yucca and Quillaya plants) have been developed for other industrial purposes and they have found some use in animal agriculture to lessen odour from manure and improve ruminal N metabolism. They are well-known as methane inhibitors (see Newbold et al. (2018) for summary), but it is equally well-known that the rumen can adapt and cleave the two components of the saponin, so that effects on methane are not persistent. Novel strategies to prevent the breakdown of saponins in the rumen (which accounts for the loss of activity) have been researched (Ramos-Morales et al., 2013) but not developed commercially.

Condensed tannins. Condensed tannins may exert several effects on rumen fermentation, including defaunation (but also decreasing fibre digestion and acting as a hydrogen sink, with the exact mechanism likely being dependant on the source or type of tannin). Effects on methane production are highly variable, and may be due to a negative effect on dry matter feed intake with increasing tannin concentration (Aboagye and Beauchemin, 2019).

GHG saving potential

Abatement	Value	Country	Reference
Monensin			
24 mg/kg DMI (Dairy cows)	-2.9% CH_4 yield	Canada	Benchaar et al., 2020

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	-	Some feed additives focused on productivity with reduced methane as a side effect
Manure CH_4	-	
Manure N_2O		
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions		
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions	?	Unknown interaction effects with other supplements
	Rating	
Confidence in mitigation effect	Low	
Cost-effectiveness**		
Confidence in cost-effectiveness		

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect

** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

Unknown

Applicability

This technology is applicable to farmed animals (cattle,sheep, pigs). These come as additives to feed so should be straightforward to apply.

Interaction effects

Relatively few studies have examined interactions between different methane-mitigating feed supplements, although we could hypothesise that supplements acting through different mechanisms might have synergistic, or at least additive effects. For example, Duthie et al. (2018) tested nitrate and distillers' grains, as a source of unsaturated fatty acids, alone or in combination. Effects on methane yield were additive. Patra and Yu (2015), working in vitro, found additive effects of nitrate, sulphate and saponin.

Barriers to research on combinations of additives include the understandable priority of technology owners to invest in their own products, and the economic challenge of using more than one mitigating agent in practice, if true synergy can be found. Further structured, hypothesis-driven study of combinations of additives is certainly scientifically justified.

A3. Rock dust
***Functional Group*: Land Management**
***Sub-Functional Group*: Nutrient Management**

Overview

Enhanced weathering of silicate rock materials contributes to the removal of carbon dioxide from the atmosphere (Beerling *et al.* 2020; Beerling *et al.* 2018). It has been proposed that crushed rock dust could be applied at large scales to cropland soils to enhance carbon dioxide removal from the atmosphere. Through weathering processes, carbon dioxide is transformed into organic carbon (mostly in the form of bicarbonate ions) which is transferred though watercourses to the oceans where the carbon is deposited and stabilised of thousands of years. Carbon may also be stored in soils in the form of carbonates. Silicate rocks such as basalt have a higher capacity for CO_2 removal than normal liming materials (calcium and magnesium carbonate), and existing infrastructure for lime application can be used to spread silicate rock dust. It has been reported that enhanced weathering has the potential to remove between 0.5–5 Gt CO_2 yr^{-1} at a global scale by 2050 (Fuss *et al.* 2018), which makes the scale of sequestration comparable with soil carbon sequestration and afforestation.

The image shows spreading rock dust in a typical arable field (Source: Yale University, 2021[11])

GHG saving potential

The main greenhouse gas saving potential from enhanced rock weathering comes from carbon dioxide removal from the atmosphere. Abatement potential by agricultural soils in the UK has been estimated between 0.2 and 0.8 tonnes of CO_2 per tonne of basic rock (Kantola, 2017; Renforth, 2012). Notably, the sequestration potential will vary depending on

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[11] Yale University Picture Archive g

the chemical composition of the rock material. Ultrabasic rocks with especially high magnesium and calcium contents can sequester > 1 tonne of CO_2 per tonne of rock applied (Kantola, 2017). There is some evidence that rock minerals may also contribute to the reduction in methane and nitrous oxide emissions from soils, whilst boosting the productivity of arable soils (Blanc-Betes *et al.* 2021; Das *et al.* 2019).

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	0	
Manure CH_4	0	
Manure N_2O	0/-	
Soil N_2O: applied N	0	
Soil N_2O: grazing	+/-	
Energy CO_2: fieldwork	+	
Energy CO_2: other	+	
CO_2 liming and urea	-	Rock dust will balance soil pH, reducing liming requirements
CO_2 sequestration below ground	-	
CO_2 sequestration above ground	0	
Pre-farm emissions	+	Mining and processing silicate rocks into dust is energy intensive
Post-farm emissions	0	
Substitution of higher C products	0	
Production increases by more than the emissions	0/-	
Confidence in mitigation effect	Medium	
Cost-effectiveness**	Low	
Confidence in cost-effectiveness	Medium	

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect

** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

Costs of rock weathering include the production and distribution of rock waste and in field application costs. Total costs have been estimated at £44–£361 per tonne CO_2 captured. Major costs are related to the energy required for transport and processing of silicate materials.

Applicability

This technology is applicable to any managed soil, provided spreading machinery can operate on the terrain. Direct application in the open ocean has also been proposed.

Interaction effects

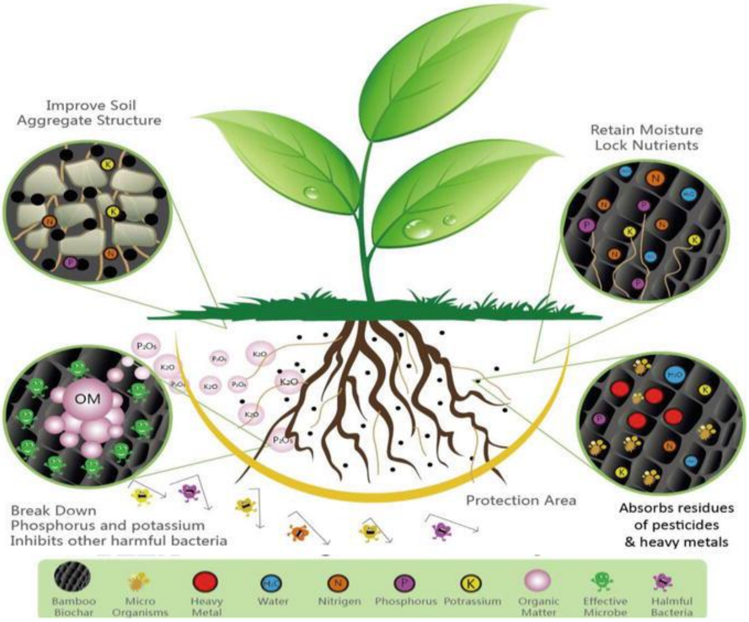
Potential benefits to plant nutrition have been reported through the application of certain rock materials, increasing the nitrogen and phosphorus nutrition of crop plants the(Jones *et al.* 2021). Rock dust from materials such as basalt also provide a substitute for lime application

A4. Biochar
***Functional Group*: Land Management**
***Sub-Functional Group*: Nutrient Management**

Overview

Biochar is a carbon rich material, similar to charcoal, produced through the pyrolysis of organic material. Pyrolysis releases half of the carbon in organic feedstocks and fixes the rest in aromatic chemical structures which resist decomposition (Lehmann, 2021). The application of biochar to agricultural soils has the potential to enhance soil carbon storage over millennia and improve soil health and crop productivity. Biochar production can also be coupled with energy generation and carbon capture and storage to produce low carbon heat and electricity.

Over the past decade, the application of biochar to agricultural soils has received considerable attention. The benefits of biochar to soil health, carbon storage, and crop productivity have been extensively demonstrated in tropical areas with degraded and dry soils (Smith, 2016). A handful of studies also indicate small benefits to crop yields across arable systems in temperate countries (Hammond, 2013). Notably, the high pH of biochar could be especially beneficial for soils in Scotland, where nearly half of all agricultural areas sampled by the Farm Advisory Service suffer from reduced productivity due to low soil pH.



The image shows the process by which biochar support plant growth (Source: Chukwuka et al., 2019[12])

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[12] Biochar A Vital Source for Sustainable Agriculture

Biochar has additional applications beyond use as a soil amendment. It is commonly used as a feed additive across Europe with proven benefits to livestock emissions, productivity, and health (Schmidt, 2019). Biochar can also be added to manures and composts to reduce emissions during decomposition, though further research is required to validate and quantify these benefits. Finally, biochar can also be included as a component of sustainable growing media for conventional horticulture and vertical farms.

GHG saving potential

Biochar production and application reduces greenhouse gas emissions by increasing soil carbon stores, reducing agricultural and energy related emissions, and improving crop productivity (Lehmann, 2021). Total GHG abatement will vary depending on organic feedstock, production technology, and predicted effects on crop yields. UK studies estimate an abatement potential of 0.7-1.4 t CO_2eq/ oven dry tonne (Hammond, 2011; Shackley & Sohi, 2010).

The challenge in confidently estimating the abatement potential of biochar as a soil amendment lies in assessing its impacts on crop productivity and soil nitrous oxide emissions (Borchard, 2019: Kammann, 2017). Many studies suggest biochar application reduces soil nitrous oxide emissions, but conflicting and divergent results suggest further research is needed to fully understand these effects. Effects on crop productivity vary with climate, soil type, and crop type, and these impacts have proven difficult to predict or explain (Lehmann, 2021).

Though the evidence base for biochar as a feed and manure additive is less developed, studies suggest significant reductions can be achieved. As a feed additive, biochar can reduce enteric methane emissions by as much as 20%, though reductions around 10% are more common across the literature (Kammann, 2017). Adding biochar to cattle slurry has been shown to reduce nitrous oxide emissions by as much as 63% (Brennan, 2015). Furthermore, biochar-containing manures may contain higher plant-available nutrients, which could further reduce emissions through enhanced crop productivity (Schmidt, 2019).

Life cycle assessment of horticultural growing media has demonstrated that replacing horticultural peat with biochar reduces emissions by 238 co2eq per cubic metre due to offset emissions from energy production and avoided emissions from peat use (Fryda, 2018).

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	-	When used as a feed additive
Manure CH_4		
Manure N_2O	-	When used as a manure additive
Soil N_2O: applied N	-	
Soil N_2O: grazing	-	
Energy CO_2: fieldwork	+	Biochar application will require fuel use
Energy CO_2: other		
CO_2 liming and urea	-	Possible reduction in liming requirements
CO_2 sequestration below ground	+	
CO_2 sequestration above ground		
Pre-farm emissions	+/-	Biochar production causes upstream emissions, but these can be offset if pyrolysis is coupled with energy production
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions		
Confidence in mitigation effect		
Cost-effectiveness**		
Confidence in cost-effectiveness		

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect
** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

The cost of biochar depends heavily on the production technology and organic feedstock used. In a 2010 study, Shackley & Sohi estimated costs from production to field application at £0–430 per tonne. The lowest cost options use water feedstocks such as garden waste, food waste, or sewage sludge. Profitability is also higher for systems which produce biochar and renewable energy. Shackley et al. 2011 estimate the cost of abatement for biochar between -144 and 208 £/tCO2.

Applicability

Biochar can be applied to any managed soil but is mainly seen as advantageous as a soil amendment for arable fields and grasslands. Alternative uses of biochar apply to other agricultural systems; biochar can be used as a feed or manure additive across livestock enterprises and as a component of sustainable growing media in indoor agriculture systems.

Interaction effects

Biochar is a relatively low-risk technology. Contaminated feedstocks could present as area of negative impacts. For example, heavy metals are not removed in the biochar production process. Additionally, carcinogenic polycyclic aromatic hydrocarbons may be produced during pyrolysis, though there is limited information available on this. Finally, potential impacts on freshwater systems related to black carbon runoff require further assessment (Tisserant, 2019).

A5. Microbial Proteins

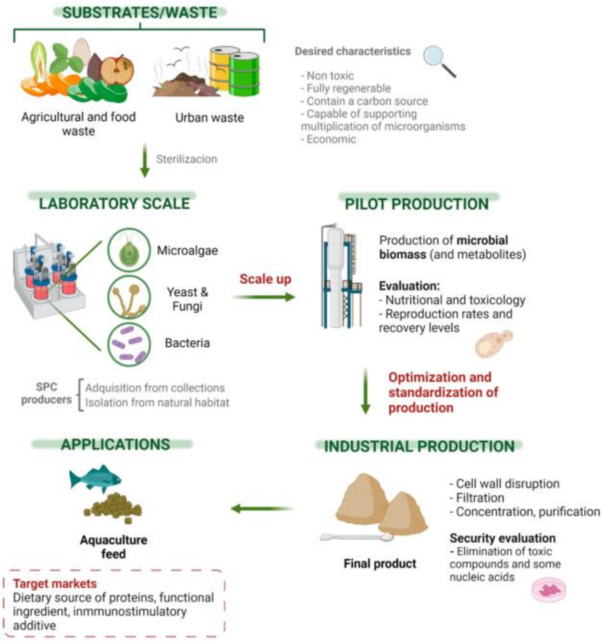
***Functional Group* : Livestock Management and Production**

Sub-functional: Alternative proteins/ Microbial proteins

Overview

Microbial protein is referred to as single cell protein (SCP), although some of the producing microbes, such as filamentous fungi or filamentous algae, may be multicellular. Single Cell Proteins are based on the continuous fermentation of micro-organisms and emerge from growing yeast, bacteria or microalgae. Their potential is in replacing mostly soya bean meal (SBM) within animal diets with the appropriate amino acid and nutritional composition. The fast growth rate of yeast and bacteria means that these organisms present a promising economical method for large-scale oil and protein production, but inputs of carbon chains are required.

Yeast and bacteria-based SCP have been included in aquaculture feed. In 1990s in Finland, it was commercialised for pig feed. SCP from yeast is being examined as a feed for dairy cattle, chickens and pigs, there is some evidence that certain species have the potential to replace in-feed antibiotics as well due to its antimicrobial properties.' Commercially available options include Feedkind Terra and Profloc (Nutrinsic Inc)



The image summarises the production process for production of single-cell proteins (SCP) (Source: Pereira et al., 2022[13])

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[13] Pereira AG, Fraga-Corral M, Garcia-Oliveira P, Otero P, Soria-Lopez A, Cassani L, Cao H, Xiao J, Prieto MA, Simal-Gandara J. Single-Cell Proteins Obtained by Circular Economy Intended as a Feed Ingredient in Aquaculture. Foods. 2022; 11(18):2831. https://doi.org/10.3390/foods11182831

Some studies have found that microalgae can be used as a protein source for lactating dairy cows in intensive milk production systems, which makes them a suitable substitution for Soya bean meal or faba beans[14].

GHG saving potential

The GHG impact has not been studied in any depth. However, is considered as a replacement for soya based meal and is therefore carbon off-setting. Some pointers that can be found in the literature is that since it does not really rely on Haber-Bosch based N fertiliser, there is much less footprint compared to protein production in conventional agriculture (Singa et al., 2021). In addition, accounting for nitrate losses from agricultural land-based protein production needs to be considered as well.

One study did look at LCA of SCP vs SBM (Spiller et al 2020) and observed the latter being worse in terms of human health impact and ecosystems impact but better in terms of resource use overall (energy-related aspects), which differed between types of SCP production systems.

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4		
Manure CH_4		
Manure N_2O		
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions		
Post-farm emissions		
Substitution of higher C products	-	Replacement for SBM though within limits
Production increases by more than the emissions		
Confidence in mitigation effect		
Cost-effectiveness**		
Confidence in cost-effectiveness		

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect
** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

[14] Top 5 soybean alternatives: 5. Single-cell protein

Cost

Costs has been estimated at £0.84-£1.60 per kg dry end product, which is more than that of soybean meal, currently trading at around £0.36 per kg(April, 2022).

Applicability

Applied to most animal sectors, including aquaculture. Each sector has its own barriers, and whilst most advances in fish feed and poultry/pigs still work to apply to ruminant sector.

Interaction effects

Unknown

A6 Underground Soil Sensors
***Functional Group* : Land Management**
***Sub-Function:* Soil Monitoring/Sensors**

Overview

Underground soil sensing uses a number of sensors and devices that can help in the real-time monitoring of soil fertility. These sensory devices incorporate various communication protocols for relaying the sensory data (Ghosh et al., 2021[15]). Essentially this means a number of sensors buried and distributed under the soil. Wireless sensors pose the least disturbance to soil structure and having fewer aboveground cables reduce the risk of undesired equipment damage and potential data loss(Levintahl et al., 2021[16]). These sensors form an array which continually monitor soil health parameters for crop growth, e.g. water and nutrient intake. The sensor usually communicates through a base station, or an echo station to increase the signal. These measures then integrate into a package which offers a dashboard of real time data and allow farmers, with an appropriate software package, to support decision making in terms of early warning system to support crop growth and consequently benefits overall yield but reduce excess inputs. Could also be coupled with other precision agriculture approaches.

The image shows the potential placing of soil sensors and their link to above ground machinery via monitoring software (Source: Soil Scout)

The product is buried underground at various depths, at shallow depth and at root depth. This depends on type of crop, e.g., cereals at 30 cms or root crops which will be deeper. Planting density is based on field characteristics but around 6 per field(?) is recommended as the base. A battery life of 20 years allows these to be buried without disturbance.

A commercially available product is recently launched but mostly tested on a small number of trial farms in Finland and specialist horticultural enterprises in South Africa. The system is

[15] Soil Fertility Monitoring With Internet of Underground Things: A Survey
[16] An underground, wireless, open-source, low-cost system for monitoring oxygen, temperature, and soil moisture

used in sports turf management, hence could be applied to intensively managed grassland systems if deemed cost-effective.

GHG saving potential

Main benefits are to improve yield per ha, by identifying interventions but also prevention of over application of nutrients and irrigation as sensors provide root health outputs. When coupled with precision farming equipment this could offer precise application of water and fertiliser.

No study on underground sensors and GHG savings exist but a number promote the idea that this would have benefits. Hence, we cannot quantify the impact but identify that savings would be on nutrient application. Also, an effect of reduced crop failure may have positive, if marginal, effects on CO^2 above ground sequestration.

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4		
Manure CH_4	-	Targeting application of nutrients
Manure N_2O	-	Targeting application of nutrients
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground	-	Effect of reduced crop lost before sprouting
Pre-farm emissions		
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions		
Confidence in mitigation effect	Low	No estimates or trials exist
Cost-effectiveness**	High	Significant cost for implementation with arguably marginal gains
Confidence in cost-effectiveness	Medium	Continued costs on subscriptions to understand metrics may not create a return.

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect
** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

Cost of a basic package of 6 sensors - estimated at around £6,000 including a 36 month subscription to the monitoring app[17]. Dependant on depth, size and characteristics it's likely that 6 sensors will not be enough to cover Scottish fields, given the variance in gradient and structure. A yearly subscription is needed to translate the sensors into a viable metric and potentially locks the farmer into a rolling contract. Presumably some linking up of data with machinery will support targeted application of fertiliser, hence data needs to be easily transferable to other manufacturers.

Applicability

Mostly applied to intensive, high value products - fruit for example, though overall this sector has a lower carbon footprint than general cropping or specialist cereals farms. If rolled out to cropping sector, then potentially would have greater applicability to root crops, in particular potatoes, which may provide a positive return on investment. Conceivably can be used on intensive grassland but may struggle to get a return.

Interaction effects

Note the technology will be water saving in dry years. There may be CO^2 emissions from power use if the decision-support tool relies on large scale computing arrays.

[17] These are costs identified by the Soil Scout System

A7 Cloud-based bioinformatics
***Functional Group* : Crop Management**
Functions: Crop improvement

Overview

Bioinformatics is defined as the application of tools of computation and analysis to the capture and interpretation of biological data. Cloud based computing platforms provide the oppourtunity to link data on plant breeding parameters and, usually apply machine learning or, in some cases, artificial intelligence, to identify patterns which then support decision making.

Cloud based platforms are either publicly available open source for scientists/breeder or commercially owned for a subscription service. Some small start-ups are appearing which target aspects such as soil biology analysis (https://biomemakers.com/), species monitoring for pest control (https://www.bioverselabs.com/) and reduction of antimicrobial resistance with engineered alternatives (https://www.next-biotics.com/technology)

There seem to be no services directed at Scottish or UK farmers generally but would require tech investment to target UK species and provide a market that provides a return.

GHG saving potential

The benefits of the systems would be to add to decision making in terms of improving crop production - yield and reduced pests - and soil health - nutrients and management - through targeted solutions.

The benefits may be offset by the carbon emissions generated from large scale computing arrays. Grealy et al (2022)[18] identified the significant power consumption needed to support analytical services but this could be managed through, e.g., renewable energy sources.

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[18] Jason Grealey, Loïc Lannelongue, Woei-Yuh Saw, Jonathan Marten, Guillaume Méric, Sergio Ruiz-Carmona, Michael Inouye, The Carbon Footprint of Bioinformatics, *Molecular Biology and Evolution*, Volume 39, Issue 3, March 2022, msac034, https://doi.org/10.1093/molbev/msac034.

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4		
Manure CH_4		
Manure N_2O		
Soil N_2O: applied N		Soil testing - though no assessment of whether this is more accurate than standard soil testing
Soil N_2O: grazing		
Energy CO_2: fieldwork	-	More precise timing of machinery runs in field
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground	-	Reduced wastage, potential higher crop yield and harvesting
Pre-farm emissions	+	Energy use from computational arrays
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions		
Confidence in mitigation effect	Low	
Cost-effectiveness**		
Confidence in cost-effectiveness		

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect

** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

Potentially subscription based model. A cost of service model may emerge for targeted advice.

Applicability

If tailored to Scottish conditions could cover all arable areas, though would need to prove better than current low-tech options, e.g. soil analysis.

Interaction effects

Should increase productivity and reduce management time

A8 Biological nitrification inhibitors
***Functional Group* : Crop management and production**
***Sub-Function:* Targeted nutrient management**

Overview

Biological nitrification inhibitors are natural products released into the soil by plants because of the release of secondary metabolites that can reduce the nitrous oxide emissions associated with nitrification by soil microorganisms (de Klein *et al.* 2022). Their action is analogous to synthetic nitrification inhibitors such as DCD which can be added to the fertiliser products to reduce nitrous oxide emissions associated with nitrification. Nitrification is known to be a significant source of nitrous oxide emissions from soils, and BNIs have been demonstrated to inhibit the conversion of ammonium nitrogen to nitrate in both field and laboratory studies. A wide range of plant species have been identified as contributing to BNI, including temperate forage species such as plantain (*Plantago lanceolata*). It is also possible to use products derived from plant materials such as Neem oil, which is widely used in India to coat urea fertilisers providing a mitigation option that is based upon nitrification inhibition. The understanding and performance of nitrification inhibitors in plant communities and their potential application for managed agricultural environments is at an early stage, and application of this technology is likely to require further research.

GHG saving potential

The greenhouse gas saving potential of BNIs is almost entirely related to their ability to reduce soil derived nitrous oxide emissions. Studies in tropical grasslands have shown a potential for BNIs to reduce N_2O emissions in the field by up to 90% (Subbarao *et al.* 2013). There is more limited evidence for the impact of BNIs in temperate systems, but work in New Zealand has shown that nitrous oxide emissions may be reduced by more than 50% for the use of plantain within species rich swards (de Klein *et al.* 2020; Luo *et al.* 2018; Simon *et al.* 2019). The mechanism of this effect is not entirely clear, as it could result from the direct effects of plant exudates on soil nitrification rates but could also result from digested forages having an impact on nitrification rates in the urine deposited by grazing livestock.

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	-	
Manure CH_4	-	
Manure N_2O	0 / -	
Soil N_2O: applied N	+	
Soil N_2O: grazing	+	
Energy CO_2: fieldwork	+	
Energy CO_2: other		
CO_2 liming and urea	-	
CO_2 sequestration below ground	-	
CO_2 sequestration above ground	-	
Pre-farm emissions	+	
Post-farm emissions	-	
Substitution of higher C products	-	
Production increases by more than the emissions	-	
Confidence in mitigation effect	Medium	
Cost-effectiveness**	High	
Confidence in cost-effectiveness	Low	

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect
** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

In most circumstances the costs would be expected to be relatively low for this mitigation measure. The implementation would be likely to involve the use of mixed swards containing plants such as plantain in grasslands. In such grassland systems costs are likely to be close to zero or potentially even negative if there are ancillary benefits of mixed swards (for example fertiliser savings or increased resilience to drought). In arable systems it could involve the use of intercropping or the application of crop residues containing biological nitrification inhibitors. In the circumstances they would be a small marginal cost but again this would depend on any ancillary benefits that were offered by the alternative management approach.

Applicability

In the first instance, use of BNIs as a mitigation option would be most likely to be applicable to grazed grasslands. This would involve the use of multi-species swards which have been demonstrated to deliver multiple benefits in terms of increased nutrient use efficiency reduce nitrous oxide emissions and increased resilience to climate change (Cummins *et al.* 2021).

Interaction effects

There is some evidence that multi species swards containing BNI's can also contribute to a reduction in methane emissions in ruminant livestock (Loza *et al.* 2021). Reductions in the rate of nitrification in soils would be expected to result in reduced nitrogen leaching, and potentially increased nitrogen use efficiency following fertiliser application. Given that this mitigation measure is dependent on natural biogeochemical cycling in the impact of existing plant species on nutrient cycles, it is unlikely that there would be any negative impacts associated with the application of this technology.

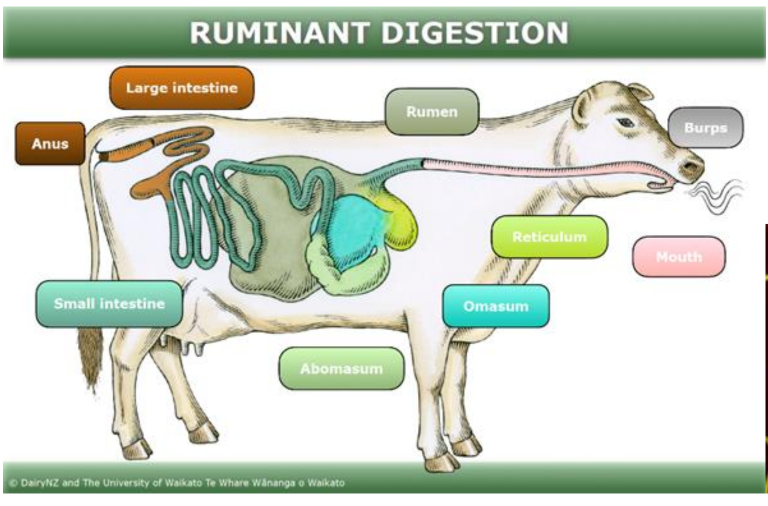
A9 Genetic profiling/Genomic testing in breeding programme

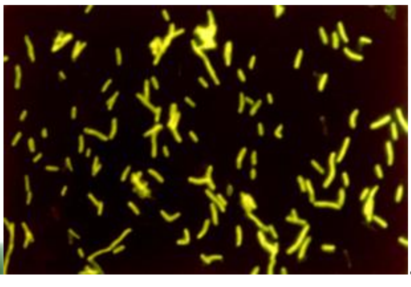
Functional Group: Livestock improvement

Sub-Function: Genetic profiling/Genomic testing in breeding programme

Overview

Genomic selection uses molecular DNA marker (single nucleotide polymorphisms, SNPs) located in the genome of animals to estimate the link between animal genomics and the traits under selection, e.g., milk yield, lifespan, fertility, to select the best animals at a younger age with higher accuracy than traditional selection (Meuwissen et al., 2001). Over the last decade, the use of genomic selection in dairy breeding programmes has more than doubled the rate of genetic gain in the net profit index of the traits under selection (e.g., United States, García-Ruiz et al., 2016; Australia, Scott et al., 2021). This genetic improvement results in a reduction in GHG emissions per kg product referred to as GHG emission intensity. Methane emissions from enteric fermentation in ruminants is the largest contributor to agricultural GHG emissions and have been reported to globally contribute to 39% of CO_2-equivalent GHG emissions from livestock (Gerber et al., 2013). In the Dutch dairy population, De Haas et al. (2021) predicted a 13% reduction in methane intensity from 2018 to 2050 using the present breeding goal, which could be increased to 24% if methane emissions are measured e.g., with sniffer technology in the milking parlour. In the UK, AHDB recently introduced a breeding index, EnviroCow that focus on traits such as cow lifespan, milk production, fertility, and feed advantage with the aim to select cows with the least GHG emissions in their lifetimes for each kg solids-corrected milk. However, the improvement could be substantially higher when methane emissions are accurately and cost-effectively measured or predicted by a proxy trait. A proxy trait accurately predicting methane emissions have been identified to be the rumen microbiome composition (Roehe et al., 2016; Auffret et al., 2018; Lima et al., 2019; Martinez-Alvaro et al., 2021). They have developed a rumen microbiome-driven breeding strategy using genomic selection which has the potential to decrease methane emissions and improve feed conversion efficiency without the need to measure those traits

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The figure shows the rumen of a cow, where methanogenic microbes (right picture) are producing methane, which is exhaled into the atmosphere. (Source: https://www.sciencelearn.org.nz/image_maps/104-ruminant-digestion)

GHG saving potential

The potential reduction in methane intensity due to existing breeding using genomic selection are predicted by de Haas (2021) to be 13% over about 30 years and can be increased to 24% using measured methane emissions using e.g., sniffer technology. As breeding is cumulative and permanent, these reductions in methane intensity due to breeding are equivalent to 0.45% and 0.88% per year, respectively.

Using genomic selection within the microbiome-driven breeding strategy, Martinez-Alvaro et al., (2022) predicted based on methane emissions of beef cattle recorded in respiration chambers of the SRUC Beef Research Centre a reduction of up to 17% per generation depending on the intensity of selection and breeding only for reduction in methane emissions. Considering that in a breeding programme using genomic selection, a generation interval of 2.25 years can be achieved, the genetic gain per generation would be equivalent to an up to 8% reduction in methane emissions per year or cumulatively up to 50% in 10 years.

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	-	Mainly targeting enteric methane emissions
Manure CH_4	-	Indirect due to improvement of feed efficiency
Manure N_2O	-	Indirect due to improvement of feed efficiency
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions		
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions	-	Selection on production and fitness traits associated with GHG emission intensity
Confidence in mitigation effect	High	
Cost-effectiveness**	High	
Confidence in cost-effectiveness	High	

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect

** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

Breeding for traits presently under selection and related to methane intensity are cost neutral. If there are more emphasis on these traits in the breeding goal, then there is expected to be a loss in genetic gain in traits not or unfavourable related to methane intensity.

Using microbiome-driven breeding has additional cost involved in taking rumen samples and analysing the samples to determine the rumen microbiome composition. However, this has to be done only for a relatively small reference population (4000 animals) and the rumen sampling could be incorporated, e.g., in beef during testing of cattle for feed conversion efficiency.

Applicability

Genomic selection is applied in all livestock species (mostly dairy, pig and poultry, at a lesser extend in beef and sheep). Microbiome-driven breeding using genomic selection is developed for ruminants to reduce methane emissions but could be also used for improvement of feed conversion efficiency and animal health traits, which are reducing methane intensity.

Interaction effects

Selection for low methane emitting animals is expected to have no negative effects on animal health and productivity as shown in a selection experiment on sheep in New Zealand (Rowe et al., 2019).

A10 Fluoride and tannin additive to manure
***Functional Group:* Livestock Management and Production**
***Sub-Functional Group:* Further Methane Management**

Overview

Manure storage and management is a significant source of national ammonia, nitrous oxide, and methane emissions. Tannic acid and sodium fluoride (TA-NaF) have been shown to eliminate the majority of ammonia and methane emissions from stored manures whilst reducing disruptive odours by half (Dalby, 2021). Tannic acid is a naturally occurring plant compound which disrupts bacterial cell membranes, while sodium fluoride acts as an inhibitor of ammonia-producing enzymes (Svane, 2020). Compared to other manure additives, such as sulfuric and nitric acids, TA-NaF contributes to greater emissions reductions and lower environmental health and human health risks (Dalby, 2020b).

Tannic acid and sodium fluoride are already produced at an industrial scale for other uses. Tannic acid is a common food additive with additional uses in wastewater treatment and medicine. Sodium fluoride is a common ingredient in dental care products and is also used as an insecticide. Their synergistic activity in reducing manure emissions is a recent discovery by researchers in Denmark as part of the "Next Generation Manure Ammonia Reduction Technology" project (Dalgaard, 2020). The product is currently undergoing further trials, and a patent application has been filed. Additional trials are needed on a range of manures and manure management systems to fully understand the impacts of TA-NaF on manure emissions.

GHG saving potential

In experiments with pig manure, TA-NaF has demonstrated a 95% reduction in ammonia emissions, 99% reduction in methane emissions, and 50% reduction in odour (Dalby, 2020b). This is a highly promising result, but other studies at lower dosages have not identified any emission reductions (Dalby, 2021). Thus, further research is needed to confidently establish the abatement potential of this technology. In addition to direct emission reductions, TA-NaF will reduce nitrogen losses from manures, improving crop productivity and potentially reducing emissions related to synthetic fertiliser use.

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4		
Manure CH_4	-	Significant reduction in manure methane
Manure N_2O		
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions	+	Embedded emissions related to chemical production
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions		
Confidence in mitigation effect		
Cost-effectiveness**		
Confidence in cost-effectiveness		

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect

** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

Major costs associated with this technology are related to high costs of tannic acid (Dalgaard, 2020). Minimum effective dosage will improve economic performance, but financial support will likely still be required for farmers to adopt TA-NaF as no clear productivity benefits have been defined.

Applicability

Major trials have mainly studied impacts on emissions from pig manure, but TA-NaF could be applicable to manures from any housed livestock system. A small set of experimental evidence suggests methane inhibition is greater for TA-NaF applied to cattle manure (Dalby, 2020a).

Interaction effects

Tannic acid is a natural product which naturally degrades faster than other manure additives. Fluoride can be toxic to wildlife and plant life at high doses, but the concentrations in treated manures do not exceed those found naturally in soils. Possible inhibitory effects on crops and soil microbiota from application of treated manures should be evaluated before widespread adoption (Dalby, 2020b).

A11. Methane Vaccine
***Functional Group:* Livestock Management and Production.**
***Sub-Functional Group:* Further Methane Management.**

Overview
In the course of microbial fermentation in the rumen H2 is produced. Methanogens (methane producing microbes) oxidise this H_2 to reduce CO_2 to form CH_4. There is currently interest, particularly in New Zealand, on the use of vaccinations to decrease the number of methanogens present in the rumen. The vaccine works by triggering an animal's immune system to generate antibodies in the saliva which then pass into the animal's rumen and suppress growth and function of methanogens.

GHG saving potential
Methane vaccines are still in the development stage, with ongoing work assessing efficacy. Summaries of saving potential, both *in vitro* and *in vivo*, are given in the "mitigation summary" section below.

Mitigation summary
Recent systematic review (Baca-Gonzalez et al. 2020) has assessed the potential of vaccines for methane reductions in ruminants (both *in vitro* and *in vivo*). Efficacy ranged from 7.7% to 69% methane reduction, there were also multiple studies which were unsuccessful *in vivo.*

Effect of vaccine production on methane emissions (table adapted from Baca-Gonzalez et al. 2020)

Effect on methane production	Compared Groups	References
12.8/14.8% [1] methane reduction *in vitro*	Sheep vaccinated with methanogen mix vs. Pre-vaccinated/vaccinated with adjuvant or PBS	*Baker et al. 2020*
26.26% [1] methane reduction *in vitro*	Sheep vaccinated with methanogens mix vs. adjuvant and PBS	*Baker et al. 2020*
Unsuccessful *in vivo*	Sheep vaccinated with mixes of three or seven methanogens vs. adjuvant and PBS	*Wright et al. 2004*
12.8% methane reduction *in vivo* 7.7% methane reduction *in vivo*, corrected for dry-matter intake	Sheep vaccinated with mix of three methanogens vs. adjuvant and PBS	*Wright et al. 2004*
Unsuccessful *in vivo*	Sheep vaccinated with mix of seven methanogens vs. adjuvant and PBS	*Wright et al. 2004*
Unsuccessful *in vivo*	Sheep vaccinated with three methanogens vs. adjuvant	*Clark et al 2004*
Unsuccessful *in vitro*	Sheep vaccinated with three methanogens plus additional methanogens vs. adjuvant	*Clark et al 2004*
Unsuccessful *in vitro*	Three semi purified IgY from hens vaccinated with three methanogens vs. semi purified IgY from prevaccinated hens	*Cook et al. 2008*
20% methane increase with anti-Methanobrevibacter ruminantium IgY 15% methane increase with anti-M. smithii IgY corrected for dry-matter disappearance	Three freeze-dried egg powders from hens vaccinated with three methanogens vs. freeze-dried egg powder from prevaccinated hens	*Cook et al. 2008*
34% methane reduction with anti-M. smithii IgY 52% methane reduction with antiMethanosphaera stadtmanae IgY 66% methane reduction with their combination, corrected for dry-matter disappearance	Three freeze-dried egg powders from hens vaccinated with three methanogens vs. freeze-dried egg powder from prevaccinated hens	*Cook et al. 2008*
Unsuccessful	Three freeze-dried egg powders from	*Cook et al. 2008*

	hens vaccinated with three methanogens vs. freeze-dried egg powder from prevaccinated hens	
49–69% reduction, corrected for dry-matter disappearance	Freeze-dried egg powder from pre-vaccinated hens vs. without egg powder addition	*Cook et al. 2008*
Unsuccessful *in vivo*	Sheep vaccinated with five methanogens vs. adjuvant and PBS	*Williams et al. 2009*
29% [1] methane reduction *in vitro*	Sera from sheep vaccinated with M. ruminantium M1 whole cells vs. prevaccinated sheep sera	*Wedlock et al. 2010*
40% [1] methane reduction *in vitro*	Sera from sheep vaccinated with M. ruminantium M1 cytoplasmic fraction vs. pre-vaccinated sheep sera	*Wedlock et al. 2010*
Unsuccessful *in vitro*	Sera from sheep vaccinated with M. ruminantium M1 wall fraction vs. prevaccinated sheep sera	*Wedlock et al. 2010*
Unsuccessful *in vitro*	Sera from sheep vaccinated with M. ruminantium M1 wall fraction with trypsin vs. prevaccinated sheep sera	*Wedlock et al. 2010*
40%[1] methane reduction *in vitro*	Sera from sheep vaccinated with derived-protein M. ruminantium M1 wall fraction vs. prevaccinated sheep sera	*Wedlock et al. 2010*
Unsuccessful *in vivo*	Goat vaccinated with protein rEhaF from M. ruminantium M1 vs. animal vaccinated with elution buffer plus adjuvant	*Zhang et al. 2015*

[1]Approximate values from article figures.

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	-	Note lack of efficacy
Manure CH_4	-	As above
Manure N_2O		
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions	-	
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions		
Confidence in mitigation effect		
Cost-effectiveness**		
Confidence in cost-effectiveness		

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect
** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost
Unknown
Applicability
Applicable to sheep, dairy and beef cattle worldwide. Possibility to be administered the same time as other routine vaccines.

Interaction effects
Unknown, still in development stage, however this will likely be assessed in the future.

A12. Smart Cattle Sheds
***Functional Group* : Livestock management and Production**
***Function:* Further methane management**

Overview

Design of a networked housed cattle system. No single definition exists but would be composed of linked up a) animal health monitoring system, b) management of microclimate, c) methane extraction. The monitoring system is connected to a low power low range wireless communication technology.

The proposed system wirelessly collects real-time information from sensors installed in the cow and the cattle shed, and the collected data are analysed by the integrated management system, delivered to the user, and automatically controlled by the application.

The image shows a modern milking shed. This highlights the opportunities for monitoring health and productivity per cow (Source: Modern Farmer, 2013[19])

A number of projects have explored the design of a shed, for instance the Cornell University's new Teaching Dairy Barn or the Tark-Laut EU funded project[20] focused on managing the microclimate with housed cattle. Animal mounted sensors (pedometers, ear-tags, collars) record activity, feeding times, temperature, rumination, and feed to a dashboard.

GHG saving potential

Claims of GHG Savings tend to focus on optimising livestock production. Ostensibly this would mean an improvement in productivity, through prevention and early diagnosis of health problems, improved welfare and energy saving on farm in terms of managing the micro-climate. Further, the SRUC Green Shed project tested extraction technology to

[19] The Dairy Barn, Redesigned
[20] Tark Laut Smart cattle housing project

remove methane and burn it through an anaerobic digester as a means to bring in a circular economy approach.

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	-	Maybe reflective of improved health and welfare status
Manure CH_4	-	Potential for removal and reuse as energy
Manure N_2O		
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other	-	Closed sheds offer chance to capture heat
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions		
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions	+/-	Applies to housed cattle, e.g. finishing beef or dairy-beef
Confidence in mitigation effect	Med	
Cost-effectiveness**		
Confidence in cost-effectiveness		

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect
** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

High capital cost would need payback over time. Mostly conducted in public sector organisations. No commercially available product is available and mostly at proof-of-concept stage.

Applicability

Applies to cattle which are housed in winter but would be reflective of intensive nature to provide a return. High technology mostly associated with dairy farming

Interaction effects

Unknown

A13. Connected animal mounted sensors
***Functional Group* : Livestock management and Production**
***Function:* Improved technical efficiencies**

Overview

The use of precision livestock farming (PLF), or agritech, tools on farm is increasing globally, with farmers utilising technology in the daily management of their herds and enterprises. When exploited to their full potential, PLF solutions can aid management and improve animal health (Neethirajan, 2017), welfare and production (Berkmans, 2014), can monitor or reduce greenhouse gas (GHG) emissions (Hammond et al., 2016), improve overall farm operational performance (Michie et al. 2020) and improve traceability of livestock products (Morgan-Davies et al., 2015), among others. However, some farmers do not utilise PLF solutions to their full potential, often utilising only a small amount of the functions available to them.

Whilst not intended to influence GHG emissions directly, PLF technologies, such as those intended to improve health and welfare, can do so by improving the efficiency of the animals and therefore the farm. There is a direct link between GHG emission intensities and animal efficiency (Grossi et al., 2018). The more efficient an animal is, i.e., the more productive, the lower the environmental impact is per unit of product, such as milk or meat (Grossi et al., 2018).

The use of PLF tools and techniques on farm not only improves the health, welfare, and production of the animals themselves, but reduces the overall carbon footprint of the enterprise. Optimising resource use by improving animal production efficiency through PLF techniques has the potential to maximise the profitability of pasture-based and housed systems and improve the environmental sustainability of ruminant production.

Mitigation summary

Whilst not intended to influence the GHG emissions of a farm, PLF technologies, such as those intended to improve fertility, can do so by improving the efficiency of the animals and therefore the farm. There is a direct link between GHG emission intensities and animal efficiency (Grossi et al., 2018). The more efficient an animal is, i.e. the more productive, the lower the environmental impact is per unit of product, such as milk or meat (Grossi et al., 2018). Technologies designed to improve efficiencies can be split into three broad categories applicable to both beef and dairy systems, and in both grazing and housed situations:

- Technologies designed to reduce slaughter age (e.g., automated weigh crates, 3D cameras, animal mounted systems to monitor intake and growth of animals)
- Animal mounted sensors designed to monitor and improve fertility. This covers oestrus detection, pregnancy detection and calving detection.
- Technologies designed to improve animal health and welfare (e.g., animal mounted sensors and accelerometers, rumen pH boluses to monitor rumen dysfunction).

Impacts of PLF introduction on whole farm emissions and emissions per unit of product have been modelled using an established carbon foot printing tool (Agrecalc; SAC

Consulting). This was carried out on both average Scottish beef and dairy farms (using data from CTS) - results are summarised below:

BEEF (spring calving upland Suckler system, Bowen et al. 2022a and b)

Five scenarios were modelled, and emissions compared to baseline: using technology to reduce slaughter age by one, two and three months, and technology designed to improve fertility, and improve health and welfare. All scenarios reduced both total farm emissions (2.4 - 7.4%) and emission intensities (1.5 - 11.9%).

DAIRY (8000L all year-round calving; Ferguson et al. 2022 and Bowen et al 2022b)

Three scenarios were modelled, and emissions compared to baseline: using technology to improve fertility, improve fertility and milk yield, and improving health and welfare. All scenarios, except improving fertility and increasing milk yields (0.7% increase), showed reductions in whole farm emissions (0.4 - 0.9%) and all scenarios reduced emissions intensities (3.0 - 9.0%).

Mitigation summary

GHG categories	Effect*	Notes
Enteric CH_4	-	
Manure CH_4	-	
Manure N_2O	-	
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions		
Post-farm emissions		
Substitution of higher C products		
Production increases by more than the emissions		
Confidence in mitigation effect	High	Information provided here is based on modelling carbon footprints of beef & dairy farms (Agrecalc). Assumptions for modelling based on published literature, communication with technology companies and expert opinion.
Cost-effectiveness**	Medium	Good ROI but over multiple years (not instantly cost-effective)
Confidence in cost-effectiveness	High	Many PLF solutions readily available on market, cost known barrier to uptake

* ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect

** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC

Cost

Cost dependent on technologies used:

£20 to £250 per animal mounted sensor plus additional cost for basestation, software, repeaters and installation (ranging from £1,000 to £10,000 depending on system/manufacturer). This includes sensors to record activity, rumination, temperature, location, pH, oestrus, health etc.

£7000 for automatic weigh crate (e.g., BeefMonitor weigh system) plus £1500 for additional solar panel system for outdoor use

Applicability

Applied to both beef and dairy cattle. Also applicable across production systems regardless of if cattle are housed or outside grazing.

Interaction effects

Systems designed to improve health etc. therefore, unlikely to have detrimental effects to the animal. Combining various technologies will increase reductions in GHG emissions observed.

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Any enquiries regarding this publication should be sent to us at

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