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On-farm technologies for the reduction of greenhouse gas emissions in Scotland

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Executive Summary

Background

This report considers 20 options for reducing greenhouse gas emissions from Scottish farms. These include changes in management of fertiliser, soil and manure, livestock feeding and energy use. Some of these changes require an investment in new tools, equipment or other installations on farm.

Considering the most cost-effective way to reduce emissions from agricultural production is an important aspect of meeting the targets set under the Climate Change (Scotland) Act 2009.

Key Findings

- The evidence indicates that individual mitigation options could reduce emissions by between 9 and 150 kt CO_2e GHG annually if they were implemented to their fullest potential extent across the country. Their cost-effectiveness is between -£112 and +£302 t CO_2e^{-1} (negative values indicate financial savings). However, this figure does not include multiple options taken together.

- Overall, the mitigation options offer other positive environmental effects (e.g. with regards to soil or water quality). Some address efficiency, reducing emission intensity through increased yields, though not necessarily reducing total emissions.

- Some well-established technologies are readily acceptable to farmers, and the main barrier in their uptake is cost. Others either require familiarisation and acceptance by farmers, or pose additional challenges that impede their implementation. The role of contractors and cooperatives is also worth considering.

- Technologies differ in terms of cost, complexity, market availability and acceptability to farmers. Some require considerable knowledge to make a sound decision and commercial availability is variable. Supporting these emerging technologies requires guidance, advice and training, in addition to financial support.

- Using a carbon (C) value threshold of £60 t CO_2e^{-1}, six of the ten assessed options are cost-effective, providing between 9 and 101 kt CO_2e mitigation.

Recommendations

We recommend that increased use of technologies is encouraged through further complementary incentive mechanisms, including:

- increased emphasis on these technologies in extension services or mechanisms;
- support for collaborative implementation of the technologies;
- foot printing/accounting schemes for validating and signalling on-farm and supply chain progress; and
- a comprehensive approach to each stage of the supply chain.

Contents

Abbreviations

AD	Anaerobic digestion
C	Carbon
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DGPS	Differential Global Positioning System
DM	Dry matter
EI	Emission intensity
EID	Electronic Identification
FR	Fertility rate
GHG	Greenhouse gas
GPS	Global Positioning System
HP	Horse power
MACC	Marginal abatement cost curve
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
PF	Precision farming
PLF	Precision livestock farming
RR	Replacement rate
VRA	Variable rate application

1 Introduction

This project was commissioned by ClimatexChange on behalf of the Scottish Government, to deliver a rapid evidence assessment on the potential greenhouse gas (GHG) abatement potential (AP) and cost-effectiveness (CE) of technological developments readily available on farm.

The report reviews 20 GHG mitigation options and related investments in commercially available machinery, equipment or buildings (technologies). The evidence includes information on the following aspects:

- GHG reduction mechanism and abatement rate of the mitigation option
- Technologies related to the mitigation option, their capital and annual costs
- Issues around the implementation of the mitigation option including current uptake
- Environmental co-effects
- Recommendations for further work

Five of these mitigation options were assessed to estimate their GHG abatement potential and costs in the Scottish context. As some of them are divided into further mitigation options, in total 10 mitigation options were analysed.

2 Results

2.1 Technology assessment

The focus of the review was the identification of technologies farmers can apply in order to reduce the GHG emissions from their farm or the emission intensity of their crop and/or livestock products (i.e. reducing emissions per unit of production). The methodology is described in Annex 1.

Annex 2 presents a brief review of each mitigation option. It summarises the GHG reduction mechanism, abatement rate, typical related technologies, implementation and uptake issues and the environmental co-effects. The related technologies sections highlight typical equipment and tools suitable for implementing the mitigation options. The lists of technologies are not exhaustive; further technologies exist, with rapidly emerging new solutions for some mitigation options. The information on current uptake is limited for most of the mitigation options due to limited existing data, particularly in the Scottish context.

The main results of the review are presented in Table 1. The mitigation options cover the major GHG emissions sources from farming activities, i.e. soil and manure N_2O, enteric and manure CH_4 and fuel CO_2 emissions, and C sequestration. Some mitigation options mainly affect NH_3 emissions, which is not a GHG, but leads to indirect GHG emissions via transformation into N_2O. Several mitigation options address efficiency, increasing crop, meat or milk yields while using the same amount of inputs, thus improving the emission intensity of production. The environmental co-effects of the options are mostly positive, improving soil, water and air quality. Some negative impacts on N_2O emissions and land use might be associated with reduced tillage and anaerobic digestion, respectively.

The technologies cover a wide range of solutions, from relatively simple replacement of fan controllers in buildings, to installation of anaerobic digesters. Capital costs range from a few thousand pounds to several millions. The annual costs (see Annex 2) are also highly variable: some technologies only incur a low maintenance cost while others require purchased materials (e.g. strong acids for slurry acidification) or subscription to information services (e.g. DGPS signal for precision crop farming) or labour costs (technical assistance for AD), all of which increase total annual costs. The cost of the technologies is in many cases not substantially higher than that of the conventional technologies (e.g. precision farming, low emission N application). Therefore when a farmer is looking to replace any of their existing equipment the additional costs of the technology with GHG mitigation benefits will be much less than the full purchase value. Some of the options enable financial savings through increased efficiency either as a reduction in resource use or an increase in yield, or via the sale of generated electricity.

Table 1 Overview of the mitigation options and examples of technologies related to them

Technology	Mitigation option	GHG reduction method	Co-effects	Constraints	Estimated cost[b] Capital (£)	Estimated cost[b] Annual (£)	Cost-effectiveness[b] £ t CO_2e^{-1}	Abatement potential[b] kt CO_2e^{-1}	Comment
Fertiliser and herbicide specialist distributer	Agroforestry (A1.1)	Soil and biomass C, soil N_2O, energy CO_2	Improved soil quality, biodiversity, reduced agro-chemical use, buffering effect of tress on the heating and cooling of the land area and livestock	Regarded as high-risk decision Low allocations of grant support for establishment are available in the current scheme	30,000	1,000	n/a	n/a	Some precision farming technologies could be used in agroforestry with some modifications
Telelifting equipment for manual pruning					45,000	1,000	n/a	n/a	
Fertiliser & sprayers for 4WD bikes					12,000	500	n/a	n/a	
VRA N fertiliser for 500 ha farm, assuming a 200 HP, GPS compatible tractor is available on the farm	Precision farming technologies (A1.2)	Soil N_2O, fuel CO_2, increased yield	Reduced pesticide use, phosphorous pollution and water use, reduced soil compaction	Time consuming data collection and analysis Incompatibilities between different PF technologies Uncertainties regarding the expected performance of PF More farmer involvement would be needed in the decision support systems	17,250	200	-112	76	Very little data for Scotland Some information on uptake in England
Auto guidance for 500 ha farm, assuming 2 tractors (200 HP, GPS compatible) are available on the farm					30,000	1,500			
Controlled traffic system					30,000	1,500			
Basic system (auto-steering, yield monitor, VRA seeding)					40,000	n/a			
Advanced system (Auto-steering, yield and protein monitor, VRA seeding, auto spray, VRA N fertilisation, VRA herbicide application)					100,000 + £22 ha^{-1}	n/a			
Site specific weed management for 500 ha farm					42,000	200			
Tractor control					10,500	n/a			
Variable rate seed drill					34,000	n/a			
Variable rate fertiliser spreader					19,500	n/a			
Trailing shoe	Low emission nitrogen application (A1.3)	Soil N_2O	Reduced NH_3 emissions from fertiliser application and manure spreading	N/A	28 – 41,000[a]	17/ha	n/a	n/a	
Trailing shoe (umbilical)					13,500[a]	17/ha	n/a	n/a	
Shallow injector					14-28,000[a]	17/ha	n/a	n/a	
Shallow injector (umbilical)					14,500[a]	17/ha	n/a	n/a	
Reduced NH_3 emission spreader					28,000[a]	14% purch price	n/a	n/a	

Technology	Mitigation option	GHG reduction method	Co-effects	Constraints	Estimated cost[b]		Cost-effectiveness[b] £ t CO_2e^{-1}	Abatement potential[b] kt CO_2e^{-1}	Comment
					Capital (£)	Annual (£)			
Pea and bean harvesters (vining peas and beans)	Legumes (A1.4)	Soil N_2O	Reduced NH_3 emissions from fertiliser application and manure spreading NH_3	Lack of yield stability Vining peas: requirement for quick delivery of the harvest to a processing plant	250,000	n/a	302	110	
direct drill	Minimum tillage and no-till (A1.5)	Energy CO_2, uncertain soil C effect, increased yield (potential negative impact on soil N_2O)	Improved soil quality and soil biodiversity, (though potentially increased need for herbicides)	Acquiring of new management skills High perceived risk Anticipated short term pest problems	30,000 – 60,000	n/a	n/a	n/a	
Installation of drainage system	Improving land drainage (A1.6)	Soil N_2O, increased yield	Improved soil quality, reduced N leaching	Regulatory issues	2,000 – 25,000 ha^{-1}	250/ha/5 yr	n/a	n/a	Significant intervention but with considerable uncertainties about abatement rates
3 leg subsoil, flat roll front discs	Alleviating and preventing soil compaction (A1.7)	Soil N_2O, increased yield	Improved soil quality	N/A	5,500	n/a	n/a	n/a	Soil type strongly affects the risk of compaction
7 leg (second hand)					13,000	n/a	n/a	n/a	
paraplough					2,050	n/a	n/a	n/a	
Feed mixer	Feed additives in total mixed ration (A1.8)	Enteric CH_4, increased yield	N/A	Adverse effects of too high levels of fat or nitrate additives No regulations for some additives Acquiring independent advice on nutrition	15,000 – 40,000	900	Probiotics: -108 Nitrate: 141 High fat diet: 186	Probiotics: 22 Nitrate: 150 High fat diet: 88	
Feed storage					200 m^{-2}				
Weighing crate	Precision feeding (A1.9)	Manure N_2O	Reduced NH_3 emissions from manure storage and spreading	Acquiring independent advice on nutrition	1,000 – 10,000		n/a	n/a	
Calving hygiene	Improved health monitoring and illness prevention: an example	All livestock emissions, increased yield	Emissions intensity of all livestock-related pollution is reduced	Potential conflict with treatments used for calf pneumonia and diarrhoea	3,000 per cavling area	n/a	n/a	n/a	

Technology	Mitigation option	GHG reduction method	Co-effects	Constraints	Estimated cost[b]		Cost-effectiveness[b] £ t CO_2e^{-1}	Abatement potential[b] kt CO_2e^{-1}	Comment
					Capital (£)	Annual (£)			
Colostrum management	of: Johne's disease (A1.10)				6,000 – 9,000	n/a	n/a	n/a	
EID readers and software	Precision livestock farming (A1.11)	All livestock emissions, yield	Emissions intensity of all livestock-related pollution is reduced	Lack of flexibility of the equipment Fear of the technology Lack of training Amount of data generated	500 – 2,300		n/a	n/a	
Weigh crate (weighing and automatic sorting of sheep)					7,500 – 10,000		n/a	n/a	
Silent herdsman – cattle heat detection (collars, base station & PC with software)					2,500 + 85 (animal to observe)$^{-1}$		n/a	n/a	
HeatWatch – cattle heat detection (patch, base station, software)					2,800 – 3,500 + £3 (animal to observe)$^{-1}$		n/a	n/a	
Robotic milking in dairy cow (auto milking system with dynamic feeding related to milk yield; ID of animals with treatment)					70,000 – 100,000		n/a	n/a	
Virtual fence (battery powered receiver on collar, induction cable & transformer)					350 + 210 animal^{-1}		n/a	n/a	
Fixed covers (retrofit possible)	Covering slurry stores and farm yard manure (A1.12)	NA	Reduced NH_3 emissions from manure storage, reduced odour	Health and safety issues of trapped gas	From 13,000	n/a	n/a	n/a	
Floating plastic plates					20 - 40 m^{-2}	n/a			
Plastic membranes					1 - 25 m^{-2}	n/a			
Lightweight expanded clay					15 m^{-2}	500			
Integral store					30 - 40 m^{-3}	n/a			
In-house acidification (for a 267 cattle dairy farm)	Slurry acidification (A1.13)	Manure CH_4	Reduced NH_3 emissions from manure storage and spreading	Handling of strong acids This technology is unknown in Scotland	70,000	4,500	5	56	
Storage tank acidification (for a 200 cattle dairy farm)					1,700 - 9,000	1,100 - 4,500			
Manure removal and drying on belts (enriched cage)	In-house poultry manure drying (A1.14)	NA	Reduced NH_3 emissions from manure storage	N/A	8-12 (bird place)$^{-1}$	n/a	n/a	n/a	Recent changes in regulations are encouraging uptake on large farms
Manure removal and drying on belts (aviary system)					10-13 (bird place)$^{-1}$	1.80-2 (bird place)$^{-1}$			
Littered system (gestating sows) (retrofit more expensive)	Low emission livestock housing (A1.	Manure storage N_2O and	Reduced NH_3 emissions from housing	N/A	47.67 – 55.41 (pig place)$^{-1}$, new build	N/A	n/a	n/a	

Technology	Mitigation option	GHG reduction method	Co-effects	Constraints	Estimated cost[b] Capital (£)	Estimated cost[b] Annual (£)	Cost-effectiveness[b] £ t CO_2e^{-1}	Abatement potential[b] kt CO_2e^{-1}	Comment
Littered system (growers-finishers) (retrofit more expensive)	15)	CH_4, energy CO_2			25.72 (pig place)$^{-1}$, new build				
Manure channel with sloped floor (weaners) (retrofit more expensive)					0.00 – 0.23 (pig place)$^{-1}$, new build				
Manure channel with sloped floor (growers-finishers) (retrofit more expensive)					0.73 (pig place)$^{-1}$, new build				
And various further technologies and building design					n/a	n/a			
AD plant	Anaerobic digestion (A1. 16)	Manure CH_4, energy CO_2	Reduced N leaching (though potentially increased competition for land)	Continuity of supply of additional feedstocks Land and crop availability for timely distribution of digestate Risk of contamination from imported feedstock Matching seasonal heat demands to CHP output Availability of electricity and/or gas grid connections Planning difficulties	1.5m for 250 kW 3.9m for 1 MWe	110 for 250 kW 250k for 1 MW (excluding crop production costs and income from electricity and heat)	Cattle manure & maize: 131 Pig & poultry manure & maize: -20 Maize only: -43	Cattle manure & maize: 37 Pig & poultry manure & maize: 9 Maize only: 22	
Electric quad bikes	Capital investment in fuel efficiency (A1.17)	Energy CO_2	Reduced air pollution from fuel use	Development of hydrogen production facilities at a farm level and associated supply chain	10,000	n/a	n/a	n/a	
Electric lift trucks					20,000	n/a			
Energy efficient fans and fan controllers	Energy efficient heating and ventilation of livestock buildings (A1.18)	Energy CO_2	Reduced air pollution from fuel use	Suitability of technologies to some buildings Long term contracts for maintenance of some technologies Uncertain continuity of government support policies Support for renewables can negate the potential financial benefits	From 1,000	n/a	n/a	n/a	
Biomass boiler					20,000	0.05 /kWh			
And various further technologies and building design					n/a	n/a			
Biomass boiler	Energy efficient crop drying (A1.19)	Energy CO_2 (grain stirrers might increase fuel use)	Reduced air pollution from fuel use	Long lifetime of existing grain dryers	20,000	0.05 /kWh	n/a	n/a	
Grain stirrers					15,000 – 20,000	n/a			
Moisture sensors					2,000 – 20,000	216-540			

Technology	Mitigation option	GHG reduction method	Co-effects	Constraints	Estimated cost[b]		Cost-effectiveness[b] £ t CO_2e^{-1}	Abatement potential[b] kt CO_2e^{-1}	Comment
					Capital (£)	Annual (£)			
Heat recovery	Energy efficient milking and milk handling (A1.20)	Energy CO_2	Reduced air pollution from fuel use	Need for the consideration of the system as a whole to improve efficiency of all parts together	>3,500	n/a	n/a	n/a	
Variable speed milk pumps				Support for renewables can negate the potential financial benefits	2,000	n/a			

[a] 2009 prices [b] n/a: not available

2.1 Abatement potential and cost-effectiveness

The individual mitigation options could reduce emissions by between 9 and 150 kt CO_2e GHG annually if they were implemented to their fullest potential extent across the country (Table 2). Their cost-effectiveness is between -£112 and +£302 t CO_2e^{-1} (negative values indicate financial savings). Using a C value threshold of £60 t CO_2e^{-1}, six of the 10 assessed options are cost-effective, providing between 9 and 101 kt CO_2e mitigation. (The C value in the UK non-traded sector is estimated to be currently £60 t CO_2e^{-1}, and is expected to increase to £74 t CO_2e^{-1} by 2030 (DECC 2011).)

The GHG abatement potential values in Table 2 are **maximum technical potentials**. For example if a policy incentive achieves 30% uptake of slurry acidification (i.e. 30% of slurry in Scotland, which is stored in tanks, is acidified), then the estimated abatement potential related to the policy is 17 kt CO_2e y^{-1}. It is also important to note that the **interactions**, which might occur should multiple options be implemented together on a farm, **are not considered**. These interactions may sometimes decrease the combined abatement potential. For example the N_2O benefits from precision farming could be reduced if 20% of the arable land were simultaneously used to grow grain legumes thus reducing the N fertiliser use on farm. The abatement potential values are indicative of **average** cost-effectiveness and abatement potential in Scotland. Due to variation in farm activities, soils, management practices and annual weather, these values are not applicable to any individual farm.

Table 2 Abatement potential and cost-effectiveness (2035, Scotland, maximum technical potential, discount rate 3.5%, interactions between the options not considered)

Mitigation measure	Cost-effectiveness £ t CO_2e^{-1}	Abatement potential kt CO_2e y^{-1}
Precision farming (crops)	-112	76
Legumes in rotations	302	110
Legume-grass mixtures	-17	101
Feed additives: Probiotics	-108	22
Feed additives: Nitrate	141	150
Feed additives: High fat diet	186	88
Slurry acidification	5	56
AD: cattle manure and maize	131	37
AD: pig and poultry manure and maize	-20	9
AD: maize only	-43	22

3 Discussion

The GHG emissions produced on farms can be reduced in various ways, including changes in fertiliser management, soil management, livestock feeding, manure management and energy use. Some of these changes require an investment in new tools, equipment or other installations on farm. This report describes selected mitigation options, the typical technological changes required and the financial implications of implementation.

Technologies differ in terms of cost, complexity, market availability and acceptability to farmers. Some require considerable effort on the part of the farmer to acquire the necessary knowledge to make a sound decision (e.g. precision farming technologies), while others impose less of a challenge (e.g. subsoiling). Their commercial availability also varies: while some of the technologies have been available for years or decades (e.g. land drainage), and are known to most farmers, others are emerging in Scotland (e.g. precision farming), or are currently unfamiliar (e.g. slurry acidification). Supporting these emerging technologies would require extensive knowledge exchange activity in addition to financial support. Some well-established technologies are readily acceptable to farmers, and the main barrier in their uptake is cost. Other technologies either require familiarisation and acceptance by farmers, or pose additional challenges that impede their implementation (e.g. existence of processing plants close enough to farms producing vining peas). An additional consideration is the role of contractors and other supply chain actors. While some technologies cannot be outsourced from the farm (e.g. a livestock building or a drainage system), some technologies are widely available via agricultural contractors or other agents in the supply chain. Typically soil cultivation and fertiliser spreading technologies belong to this group (fertiliser spreaders, cultivators, harvesters, some precision farming activities), but it is also possible to obtain some livestock feed mixing requirements via the feed companies, or for many farmers a farm co-operative does the crop drying, so energy efficient measures would be implemented by the co-op. Accordingly various actors in the supply chain potentially need to be involved to maximise uptake of these technologies.

4 Recommendations

Existing policy instruments (e.g. Farming for a Better Climate[1], the forthcoming Beef Efficiency Scheme[2]) currently support GHG mitigation to some extent. Proposals in RPP2 (Scottish Government 2013) might offer potential mechanisms in the future. However, if increased use of technologies is necessary, we suggest that further complementary incentive mechanisms need to be implemented. Suggestions include: a) increased emphasis on these technologies in extension services or mechanisms; b) support for collaborative implementation of the technologies; c) foot printing/accounting schemes for validating and signalling on-farm and supply chain progress.

[1] https://www.sruc.ac.uk/info/120175/farming_for_a_better_climate
[2] https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/beef-efficiency-scheme/

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Annex 1: Description of mitigation options and related technologies

A1.1 Agroforestry

A1.1.1 GHG reduction mechanism

Agroforestry includes silvo-arable systems combining woody vegetation with arable crops, silvo-pastoral systems where woody vegetation and grass is combined and woody vegetation planted as buffer zones. The woody vegetation can be trees or shrubs and can be used for timber, fuel or fruit. There is increasing interest in Europe in combining agriculture with short rotation coppice.

GHG mitigation mechanisms of these systems include reduced fossil fuel consumption through reduced machinery use in areas with trees and reduced fertiliser and agrochemical use due to the reduced land area under crops. Trees may also increase the efficiency with which fertiliser N is used due to the different rooting depths and patterns of trees and pasture/arable species (Bergeron *et al.* 2011). This could also reduce the soil N readily available for the production on N_2O (Thevathasan and Gordon 2004) and reduce downstream N_2O losses by reducing leaching (Anon. 2009). The use of either leguminous tree species or leguminous understorey species can additionally reduce the need for fertiliser N per unit area. There will also be a buffering effect of tress on the heating and cooling of the land area and the provision of shelter may reduce the need for heating/cooling of buildings. Enhanced forage quality can also reduce CH_4 emissions from ruminant livestock.

There is also evidence of increased carbon storage in agroforestry systems compared with conventional agriculture, for example, a 79% increase in fine root carbon in silvo-arable compared to arable (Upson and Burgess 2013). A mean carbon sequestration of 0.1–3.0 t C ha^{-1} y^{-1} over a 60 year period through immobilization in trees in European agroforestry systems has been estimated by Palma *et al.* (2007). Hamon *et al.* (2009) suggest annual sequestration of 1.5–4 t C ha^{-1} for tree densities of 50–100 ha^{-1}.

A1.1.2 Abatement rate

Table 3 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Soil N_2O	Improved N use and reduced fertiliser: 0.20 t CO_2e ha^{-1} yr^{-1}	Canada	(Thevathasan and Gordon 2004)
C sequestration	10.08 t CO_2e ha^{-1} yr^{-1}	European average estimate	(Aertsens *et al.* 2013)
C sequestration	Conversion of grassland to silvo-arable: no net change		(Upson 2014)
C sequestration	Conversion of arable to silvo-arable 1.5 t CO_2e ha^{-1} yr^{-1}		(Upson 2014)

A1.1.3 Related technologies

In addition to the need to plant, cultivate and eventually harvest trees in traditional agroforestry (silvo-arable or silvo-pastoral) systems, the intercrop of cereals or grass has to be managed in a more fragmented manner. With rapid uptake of technology for auto-steer, precision fertiliser and precision fungicide/pesticide in conventional agriculture, the same technologies to precisely manage within the cropped areas is also becoming available but will need augmentation. For example auto-steer works well within standard fields, with standard gateways and some within-field avoidances (solitary trees, ditches), so 'alley way' agroforestry poses few intrinsic problems. The key issue would be uploading of mapping data for any tree alley locations or areas of trees with a regular matrix. For more informally laid out silvo-arable systems, fertilising and other tractor-based work of grassland creates more issues for tractors, and more opportunities for location-based precision to be more efficient. Low ground pressure equipment to reduce root damage is important. For smaller scale operations, especially in silvo-pastoral systems, small size 4WD pulled equipment may be the most suitable (McAdam *et al.* 2009). There are high labour demands for agroforestry systems, with pruning being critical to development of potentially higher quality timber. Specialist agroforestry systems (fruit, chickens etc.) will all have specific requirements for machinery. Some examples of equipment and costs are presented in Table 5.

Table 4 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Precision agriculture	Machinery that can accurately apply fertilisers and herbicides	*circa* £30,000	*circa* £1,000 y^{-1}	
Pruning technology	Telelifting equipment for manual pruning with potential for automation	*circa* £45,000	*circa* £1,000 y^{-1}	
4WD trailed equipment	Fertiliser and sprayers for 4WD bikes	*circa* £12,000	£500 y^{-1}	

A1.1.4 Issues around implementation, current uptake

The uptake of agroforestry is limited by a number of factors including risk perception, locally relevant knowledge and advice and lack of incentives. There are continued issues regarding the ability for agroforestry systems to be integrated into Common Agricultural Policy payment systems, particularly within the UK. Within each of the UK home countries there have been differing definitions of eligibility under previous systems and only low allocations of grant support for establishment are available in the current scheme. None of this enhances confidence amongst the land use community. However, the potential for inclusion of agroforestry is high where trees can be introduced into existing landscapes without the need for major change. Increasing interest in the nutritional benefits of novel crops such as top fruit and barries also offer potential for new opportunities in agroforestry.

A1.2 Precision farming technologies

A1.2.1 GHG reduction mechanism

Precision farming (PF) refers to a range of rapidly developing farming technologies which provide more precise information about the managed resources and allow variable management of them. PF originated in crop farming, but livestock and grass applications are rapidly growing. This section is about crop PF; for livestock applications see Section A1.11.

The range of PF technologies can be categorised as recording technologies, reacting technologies and guidance technologies, all relying on some form of geographical positioning systems (GPS), e.g. differential GPS (DGPS) (Figure 1).

Both the purpose and the complexity of PF technologies vary considerably. A farmer implementing PF would choose a combination of technologies, most often starting with a basic system enabling more accurate manual speed control and steering based on low accuracy GPS and visual aids to reduce overlaps in field operations. More complex systems are capable of 10 cm accuracy auto-steering, yield monitoring and mapping and variable rate application (VRA) of pesticides, fertiliser, etc. The most sophisticated systems have even higher accuracy and collect more data (e.g. soil maps, biomass index).

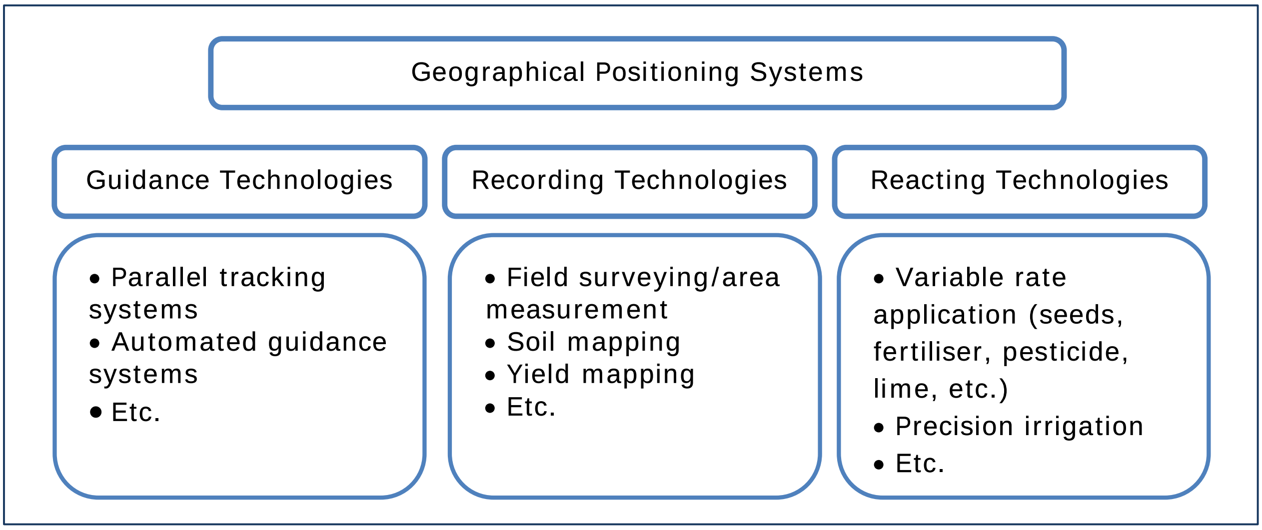

Figure 1 Categories of PF technologies (Schwartz et al. 2010)

PF technologies improve efficiency by reducing the amount of resources used per unit of yield, thus reducing the GHG emission intensity of the products. Apart from the life cycle emissions embedded in the different resources (e.g. the energy used to produce pesticides, the energy and N_2O emissions from N fertiliser production), two resources stand out as important factors in the GHG mitigation effects of PF: N fertiliser and fuel. Variable rate N fertiliser application (both synthetic N and animal waste) improves N use efficiency on farms, increasing the yield and/or reducing the amount of N applied, thus reducing N_2O emission intensity and/or emissions per area. Guidance technologies reduce the overlap in field operations, thus reducing fuel use and associated on-farm and embedded GHG emissions.

A1.2.2 Abatement rate

Table 5 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Soil N_2O	-68% N fertiliser use (winter wheat)	USA	In a review by Diacono *et al.* (2013)
Soil N_2O	-59 – -82% N fertiliser use (winter wheat)	USA	In a review by Diacono *et al.* (2013)
Soil N_2O	+15% N use efficiency (winter wheat)	USA	(Raun *et al.* 2002)
Soil N_2O	-10 – -12% N fertiliser use (winter wheat)	Germany	In a review by Diacono *et al.* (2013)
Soil N_2O	0.46 t ha^{-1} yield increase (winter and spring wheat)	Germany	In a review by Diacono *et al.* (2013)
Soil N_2O	-0.02 – -0.621 t CO_2e ha^{-1}	Germany	From various sources in Frelih-Larsen *et al.* (2014)
Soil N_2O	-0.2 t CO_2e ha^{-1}	UK	(Moran *et al.* 2008)
Soil N_2O	-57% N fertiliser use (forage maize)	UK	(Mantovani et al 2011)
Soil N_2O	-2% fertiliser use	US	(Shockley *et al.* 2011)

Abatement	Emission reduction	Country	Reference
Fuel CO_2	-10% fuel use	US	(Shockley *et al.* 2011)

A1.2.3 Related technologies

Some examples of the costs of basic and more advanced PF systems are presented in Table 7.

Table 6 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
VRA N fertiliser for 500 ha farm, assuming a 200 HP, GPS compatible tractor is available on the farm	DGPS mounted on tractor (5 years lifetime)	£250	Maintenance: £200 y^{-1}	(Tavella *et al.* 2010)
	Board computer/task controller (5 years lifetime)	£1,000		
	Yara N-sensor with extra equipment for the spreader (10 years lifetime)	£16,000		
	Total annualised cost:	£6 ha^{-1} y^{-1}		
Auto guidance for 500 ha farm, assuming 2 tractors (200 HP, GPS compatible) are available on the farm	Claas equipment for the tractor (DGPS, screen, controller) (5 years lifetime)	2*£15,000	Maintenance: 2* £200 y^{-1}	(Tavella *et al.* 2010)
	Subscription of Geoteams Real Time Kinematic (RTK) signals	-	£1,100	
	Total annualised cost:	£17 ha^{-1} y^{-1}		
Controlled traffic system	Same as auto guidance			(Tavella *et al.* 2010)
Basic system	Auto-steering (2cm accuracy), yield monitor, VRA seeding	£40,000	No information	(Jochinke *et al.* 2007)
Advanced system	Auto-steering (2cm accuracy), yield and protein monitor, VRA seeding with depth control, auto spray, VRA N fertilisation, VRA herbicide application (5-20 years lifetime)	£100,000	No information	(Jochinke *et al.* 2007)
	Gamma radiometric survey, soil grid maps, electromagnetic soil survey, consultant costs (10-20 years lifetime)	£22 ha^{-1}	NA	
	Remote sensed biomass index, leaf area index	NA	£8 ha^{-1} y^{-1}	
Site specific weed management for 500 ha farm, assuming a 200 HP, GPS compatible tractor is available on the farm	DGPS mounted on tractor (5 years lifetime)	£250	Maintenance: £200 y^{-1}	(Tavella *et al.* 2010)
	Board computer/task controller (5 years lifetime)	£1,000		
	Weed map creation (@ £23 h^{-1} consultant cost)	£80		
	Weed detection (@ £23 h^{-1} consultant cost)	£400		
	Lindus injection sprayer (12 years lifetime)	£40,000		
	Total annualised cost:	£11 ha^{-1} y^{-1}		
Tractor control	New Holland T7030 Guidance equipment	£10,500		Supplier (Lloyds)

Technology	Short description	Capital cost	Annual costs	Reference
Variable rate seed drill	Seed drill Amazone ADP Super 3m	£34,000		Supplier (Lloyds)
Variable rate fertiliser spreader	Fertiliser spreader Amazone ZATS 3200	£19,500		Supplier (Lloyds)

A1.2.4 Issues around implementation, current uptake

Apart from the obvious barrier of high investment costs, farmers have a number of other concerns regarding PF technologies that prevent them from adopting (further) technologies. These include that data collection and analysis can be time consuming, incompatibilities between different PF technologies and uncertainties regarding the expected performance of the systems (Pedersen *et al.* 2004). The same authors also argue that farmers should be more involved in the development of technologies and decision support systems. According to a German study, the main motivating factors for adoption are financial benefits and better knowledge of the fields (Reichardt and Jurgens 2009).

English data show that between 2 and 22% of farms used various PF technologies in 2012: 22% of them used GPS (including auto-steering), 20% and 11% used soil and yield mapping, respectively, 16% used VRA and 2% using telemetry (Defra 2013a). The uptake increased 20% to 200% for the different technologies between 2009 and 2012 (Defra 2009). Uptake rates are highest for cereal and cropping farms, and increase with farm size. Relevant Scottish data were not available.

With the further improvement of PF technologies and a reduction in their costs uptake can be expected to increase in future. However, this increase can be accelerated and directed towards GHG mitigating technologies by policy support.

A1.2.5 Environmental co- effects

With an improved resource efficiency provided by PF technologies a wide range of negative environmental effects can be reduced, including nitrate leaching, phosphorous pollution, pesticide pollution, improving soil and water quality and on-farm biodiversity. Controlled traffic systems improve soil quality due to reduced overall compaction. Additionally, precision irrigation technologies allow better water use efficiency in cropping activities.

A1.2.6 Recommendations for further work

The uptake of and farmers' perceptions on PF technologies in Scotland has not been explored. Existing evidence has focused on countries with a high proportion of cropland and large farms. The predominance of general cropping, mixed and dairy farms requires consideration of if wider adoption of PF is the aim.

Note also that data on the GHG, N use and fuel use effects of PF technologies is scarce; additional experimental, modelling and survey work would allow a more robust characterisation of these effects, guiding stakeholders towards the technologies providing highest GHG mitigation.

A1.3 Low emission nitrogen application

A1.3.1 GHG reduction mechanism

Low emission N application methods reduce ammonia (NH_3) emissions from slurries, farm yard manure and liquid synthetic fertilisers by minimising the contact of fertiliser with air and increasing the infiltration to the soil. Trailing hose spreaders apply slurry in narrow bands on top of the surface, while trailing shoe applicators have shoe-like attachments to deposit the slurry below the crop canopy. Injection techniques make shallow or deep cuts in the soil where slurry or other liquid fertiliser is placed. Injectors are generally more effective than band spreaders in reducing NH_3 emissions, and the efficiency of the band spreaders is affected by the height of the crop. As a result of the lower NH_3 emissions indirect N_2O emission is reduced, at the same time more N becomes available to the crop, and direct N_2O emissions are also affected.

A1.3.2 Abatement rate

Table 7 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Direct N_2O	Band spreader: 0%	UK	Unpublished data
Direct N_2O	Band spreader: 0%	UK	(Bell *et al.* 2016)
Direct N_2O	Emissions likely to increase		(Webb *et al.* 2010)
NH_3	Band spreader: 0%	UK	(Bell *et al.* 2016)
NH_3	Band spreader: -51 – -53%	Switzerland	(Hani *et al.* 2016)
NH_3	Band spreader: -60% Injector: -80%	Ireland	http://www.teagasc.ie/research/reports/environment/4783/eopr-4783.asp
NH_3	Trailing hose: -35% (0% – -75%) Trailing shoe: -65% (-38% – -74%) Injector: -70% – -80% (-23% – -99%)		(Webb *et al.* 2010)
Yield	Band spreader: +£5 ha^{-1} Injector: +£9 ha^{-1}	UK	http://farmnw.co.uk/factsheets/cost_effective_slurry_spreading
Yield	Injector: -4% – -8%	Sweden	(Rodhe and Halling 2015)

A1.3.3 Related technologies

Table 8 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Trailing shoe	Various specifications by various makers	£28,000 – £41,000 in 2009		(Webb *et al.* 2015)
Trailing shoe	Umbilical (maker: Tramspread/Joskin)	£13,500 in 2009		(Webb *et al.* 2015)
Shallow injector	Various specifications by various makers	£14,000 – £28,000 in 2009		(Webb *et al.* 2015)
Shallow injector	Umbilical (maker: Spreadwise)	£14,500 in 2009		(Webb *et al.* 2015)
Reduced NH_3 emission spreader	Average of price quotes	£28,000	Maintenance: 14% of purchase price	(Webb *et al.* 2015)

Technology	Short description	Capital cost	Annual costs	Reference
	Additional spreading cost		– £2.15 £0.52 – £0.65 m^{-3} slurry	
Injector	Contractor costs of using an injector		£17 ha^{-1}	http://farmnw.co.uk/factsheets/cost_effective_slurry_spreading

A1.3.4 Issues around implementation, current uptake

Farmers typically own splash plate slurry applicators, and therefore would normally need to invest in new machinery or switch to using contractors.

A1.3.5 Environmental co- effects

There is a reduction in odours when either band spreaders or injectors are used. They also can result in an increase in yield and the energy content of the grass because the N loss is decreased. The increase in yield ranged from 10% for band spreaders to 17% for injectors (http://farmnw.co.uk/factsheets/cost_effective_slurry_spreading). Potentially this could be translated into a reduction in the application rates of inorganic fertiliser with the associated reduction in N_2O emissions. In terms for grass production, it would be more financially rewarding for the farmer to either reduce the input of purchased concentrates or increase the liveweight gain of the livestock (http://farmnw.co.uk/factsheets/cost_effective_slurry_spreading). On the other hand, injectors can damage the crop and result in a yield penalty of between 4-8% (Rodhe and Halling 2015).

A1.3.6 Recommendations for further work

Further work is required to quantify the benefits in terms of ammonia emissions and N_2O with respect to the weather at the time of slurry application. There is also a need to establish the effect of the method of application on crop yield.

A1.4 Legumes

A1.4.1 GHG reduction mechanism

Legumes are understood to provide a significant opportunity to achieve the mitigation of GHG emissions in agricultural systems (Luescher *et al.* 2014, Moran *et al.* 2008). Legumes are grown in farming systems in a variety of ways; as mixtures in grass/clover leys, as intercrops (e.g. for peas and cereals grown together for whole crop forages), in pure stands (where peas and beans are often grown as forage crops) and as a horticultural crop (for human consumption). The principle by which mitigation is achieved is the same. Legumes are able to fix atmospheric N, and therefore have less dependence on synthetic N fertilisers. Unlike synthetic fertilisers, the N fixed by biological N fixation is not considered to be associated with GHG emissions (these occur both from the manufacture of synthetic fertilisers and from the soil after they are applied to crops). In circumstances where legumes displace imported protein crops such as soya, there can also be reduced indirect emissions of GHGs associated with indirect land use change.

A1.4.2 Abatement rate

A recent review estimated the abatement potential of increasing grass clover leys and planting grain legumes to be around 0.5 t CO_2e ha^{-1} y^{-1} (MacLeod *et al.* 2010b). Both measures were associated with a high level of agreement amongst experts regarding mitigation potential. A recent French study reported a rather higher potential for mitigation by grain legumes of 1.6-2.0 t CO_2e ha^{-1} y^{-1}, (including upstream emission savings and expressed for the area of the legumes rather than the whole rotation) but similar levels of mitigation by grass clover leys (0.4 t CO_2e ha^{-1} y^{-1}) (Pellerin *et al.* 2013).

A1.4.3 Related technologies

The costs of implementation depend upon the circumstances in which the legume is being used. Forage crops, grown as mixtures or as single crops require no specialist equipment, since grass clover leys and cereal/legume mixtures would normally be cut and stored using standard farm equipment. Vining peas and beans require specialist harvesting machinery, with harvesters often costing upwards of £250,000.

A1.4.4 Issues around implementation, current uptake

Legumes are commonly grown for forage in Scotland, and the barriers to cultivation of these crops would not be linked to mechanisation issues. However, the area of combinable peas and beans is small and declining, with recent Scottish Government statistics reporting that less than 4,000 ha was grown in Scotland in 2014 (Scottish Government 2015a), with a further 8,000 ha peas and beans grown for human consumption. Barriers to undertake include the lack of yield stability and lower gross margins in the case of grain legumes, and in the case of grass clover leys, lower yields and difficulties in establishment of productive grass clover swards (Rees *et al.* 2014).

A further constraint on the cultivation of vining peas is the requirement to be able to deliver harvested peas to a processing plant within 150 minutes of harvest. There are currently only 8 freezing plants and one canning factory that are able to accept harvested peas in the UK (PGRO 2016).

A1.4.5 Environmental co- effects

The biological fixation of N by legume crops leaves nutrient rich residues in the soil that provide a benefit to subsequent crops within a rotation. This benefit is often underestimated by farmers, but can provide a significant financial benefit when the costs of reduced fertiliser application are accounted for (Bues *et al.* 2013).

A1.4.6 Recommendations for further work

There is a need to explore opportunities to increase legume production in Scottish agricultural systems, in order to improve protein security and to achieve environmental gains. In order to achieve this, the relative value of regulatory approaches and voluntary measures should be explored.

A1.5 Minimum tillage and no-till

A1.5.1 GHG reduction mechanism

The reduction or omission of cultivation in reduced till or no-till decreases the mixing and disturbance of soil organic matter so that the respiration rate of organic carbon can be reduced and carbon fixed from the atmosphere by photosynthesis may accumulate. This option has been promoted in the past decade as being important for climate change mitigation due to C sequestration. However there is no real clear evidence that no-till can lead to C sequestration let alone climate change mitigation (Powlson *et al.* 2014, VandenBygaart 2016). No-till and reduced tillage can increase organic matter in the top 30 cm, but not necessarily below this depth, where it continues to accumulate under ploughing.

Nitrous oxide emissions can also override any possible mitigation effect due to C sequestration. In Scotland N_2O emissions tend to increase with no-till/reduced tillage in wet soils. Conditions for favourable gas exchange regarding N_2O are stable structure and good drainage. These conditions are favoured by addition of soil organic matter with a significant labile fraction (e.g. short term leys) and by compaction control (Ball 2013). In Scotland, a potential way for reduced tillage and no tillage practices to succeed is to use some form of traffic control[3] (see also Precision farming technologies) so that cropped soils can be kept relatively dry. Crops grown in traffic free lanes where soil structure and hydrology can improve can allow for reduction in greenhouse gas emissions (Tullberg 2010).

A1.5.2 Abatement rate

Table 9 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Soil CO_2	0 – 4.7 t CO_2e ha^{-1} yr^{-1} cf. conventional ploughing	Various in Europe	In a review by Soane *et al.* (2012)
Soil CO_2	0 – 4.0 t CO_2e ha^{-1} yr^{-1} cf. conventional ploughing	Various with wet/cool climate	In a review by Abdalla *et al.* (2013)
Soil N_2O	-0.9 – 0.3 kg C ha^{-1} yr^{-1} cf. conventional ploughing	Various with wet/cool climate	In a review by Abdalla *et al.* (2013)
Soil CH_4	Evidence weak and effect minor	Various in Europe	In a review by Soane *et al.* (2012)
Soil CH_4	Evidence weak and effect minor	Various with wet/cool climate	In a review by Abdalla *et al.* (2013)
Fuel CO_2	0.05 – 0.14 t CO_2e ha^{-1} yr^{-1} cf. conventional ploughing -50 – -84% (20-53 litre ha^{-1}) of fuel use during field cultivation, using GHG conversion factor of 2.56 kg CO_2e $litre^{-1}$ (average biofuel diesel blend) Defra[4]	Various in Europe	In a review by Soane *et al.* (2012)

A1.5.3 Related technologies

Table 10 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Minimum tillage	Shallow cultivators	Use of contractors to establish crops is common		Sumo, Vaderstad
No-till	Direct drill	£30,000 – £60,000		John Deere, Claydon

[3] http://www.controlledtrafficfarming.com/Home/Default.aspx
[4] http://www.ukconversionfactorscarbonsmart.co.uk/

A1.5.4 Issues around implementation, current uptake

Reduced and no-tillage can save time (labour costs) and machinery costs though these may be offset by increased herbicide costs due to the more challenging agronomic conditions. Overall, reduced costs are a main driving force behind adoption across Europe (Lahmar 2010). The most important barriers are the cost of the equipment, acquiring of new management skills, high perceived risk and anticipated short term pest problems (Knowler and Bradshaw 2007).

In England in 2010 adoption of zero tillage technique was 4% of total cultivated area while 40% of the area was reported to be cultivated with reduced or minimum tillage techniques (at least 30% of stubble, crop residue left on surface) (Defra 2010). Scottish data available in the Eurostat database[5] shows that 6% and 7% of arable land is cultivated with conservation and no tillage techniques, respectively.

Practical guidance for the Scottish circumstances can be found in the SAC Technical Note on minimum tillage[6].

A1.5.5 Environmental co- effects

Reduced and no-tillage is usually found to increase soil biodiversity and contribute to erosion control. Their effects on phosphate and nitrogen losses are variable (Soane *et al.* 2012), and these techniques might require increased herbicide use.

A1.5.6 Recommendations for further work

Experimental work on emission and mitigation of GHGs would benefit from a focus on several gases simultaneously (N_2O, CO_2, CH_4). Short term studies of CO_2 and CH_4 exchange need better linkage to long-term studies of C sequestration.

A1.6 Improving land drainage

A1.6.1 GHG reduction mechanism

Improved drainage can increase productivity and reduce emissions of N_2O (both expressed on a unit area and unit product basis) and it is also important for climate change adaptation. The effect of drainage on net GHG emissions is complex. When fertiliser nitrogen is applied to wet soils, it can be expected that N_2O emissions will increase relative to those in well-drained soils. However increased wetness can also inhibit soil respiration and so lead to decreased CO_2 emissions. Whether or not this leads to an increase in soil organic matter depends upon the balance of CO_2 release and carbon input through photosynthesis. Results from the analyses of over 2000 topsoil samples from the Scottish Soils Database gave no clear indications that wetter (that is, imperfectly or poorly drained) soils were more likely to have greater concentrations of soil organic carbon than drier, freely drained soils (Lilly *et al.* 2012). The overall effect on GHG balances is thus difficult to predict, the emissions are neither spatially nor temporally uniform and will vary with climate and farm type/enterprise.

[5] http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do
[6] http://www.sruc.ac.uk/downloads/download/583/tn553_minimum_tillage

A1.6.2 Abatement rate

Given the complexities of the mechanisms responsible for greenhouse gas abatement through the implementation of drainage, there are considerable uncertainties about abatement rates. A recent review estimated the abatement potential of improved land drainage to be around 1 t CO_2e ha^{-1} y^{-1} (MacLeod *et al.* 2010a).

A1.6.3 Related technologies

The installation of new drainage systems is a specialist operation, and is associated with high costs. Typical installation costs of new land drainage have been reported in range between £1,800 – £2,000 ha^{-1}, with ongoing maintenance costs of £250 ha^{-1} every five years (MacLeod *et al.* 2010a). However, in a small recent survey farmers noted that installation costs can be greater than £25,000 ha^{-1} (Lilly *et al.* 2012).

A1.6.4 Issues around implementation, current uptake

In a recent CxC report farmers identified cost as the biggest single barrier to the installation of new drainage systems (Lilly *et al.* 2012). Farmers reported that they would undertake emergency repairs, but long-term maintenance and renewal of the systems were of lower priority. Some farmers also noted regulatory issues as a barrier (in particular CAR General Binding Rules). The same authors contacted three of the larger drainage contractors in Scotland using a questionnaire. There was agreement on that the current state of drainage in Scotland is poor. They reported low rates of installation (< 100 ha y^{-1}) and expected further decline in the future. Farmer's views were consistent with those expressed by the contractors (Lilly *et al.* 2012).

Although there is recognition that drainage provides a range of benefits in agricultural soils, three is also increasing concern that drainage of organic rich soils can have deleterious effects on a range of ecosystem services including carbon storage and biodiversity. This concern has led to a number of policies and guidelines discouraging drainage of organic rich soils and wetlands. These include the Scotland Rural Development Programme, Farming for a Better Climate scheme and Flood Risk Management (Scotland) Act 2009.

A1.6.5 Environmental co- effects

Drainage is a significant land management intervention with the potential to impact on a range of functions both directly and indirectly in ways that are not always intended. For example the installation of artificial drainage systems into cultivated and fertilised land can increase nitrate and phosphorus leaching to surface waters by increasing the rate of runoff. It will also have the potential to alter river flows, which will be more marked in those catchments with a high proportion of cultivated land and with soils with inhibited drainage. Conversely, nitrate leaching to groundwater may be reduced as soil hydraulic conductivity is greatest when the soil is saturated; artificial drainage schemes will reduce the length of time a soil is saturated. Although there is recognition that drainage provides a range of benefits in agricultural soils, there is also increasing concern that drainage of organic rich soils can have deleterious effects on a range of ecosystem services including carbon storage and biodiversity.

A1.6.6 Recommendations for further work

There is a need to undertake a survey of the current status of drainage systems in Scotland in order to be able to fully quantify the ability of this measure to contribute to GHG mitigation. However it is also important to recognise that well-functioning drainage systems are critically important to the productivity and could be seen as an adaptation to projected climate change.

A1.7 Alleviating and preventing soil compaction

A1.7.1 GHG reduction mechanism

Soil compaction has been reported to increase N_2O emissions (Ball *et al.* 1999, Cranfield University *et al.* 2007) as a result of the soil becoming anaerobic and therefore promoting the dentrification process. Hence, reducing soil compaction and preventing its reoccurrence can reduce GHG emissions as well as leading to improved soil function and potentially increased yield. In order to avoid compaction, better planning of field operations on wet soil is required (Frelih-Larsen *et al.* 2014). Soil type strongly affects the risk of compaction, sandy soils are the least susceptible when the soil water content reaches field capacity, while clay soils are the least sensitive to compaction under soil dry conditions (Fleige *et al.* 2002). In order to avoid soil compaction in the long-term, regular assessment of the drainage is required, and improvements made as and when required. In the case of moderate compaction, cultivation of the soils would be appropriate. However, if the soils are more severely compacted, sub-soiling of arable land or ploughing and reseeding of grasslands would be necessary.

A1.7.2 Abatement rate

Table 11 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Direct N_2O	-25% – -65% at plot level	UK	(Ball *et al.* 2000)
Direct N_2O	-0.05 t CO_{2e} (roughly equivalent to 6% reduction in E_1)	UK	(Moran *et al.* 2008)
Direct N_2O	-20% – -50%	The Netherlands	(Mosquera *et al.* 2007)
Direct N_2O	-100 kt CO_{2e}	UK	(Gooday *et al.* 2014)

A1.7.3 Related technologies

For moderate compaction, standard ploughing will reduce the compaction and therefore potentially reduce N_2O emissions. To alleviate deeper compaction, sub-soiling will be required.

Table 12 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Deep ploughing	Loosen and break up soil at depths below the level of a traditional ploughing (depth of 30 cm)		Contractor cost: £70 ha^{-1} y^{-1}	http://www.naac.co.uk/userfiles/files/contracting%20charges%202014-15.pdf
Sub-soiling	Loosen and break up soil at depths below the level of a traditional ploughing (depth >50 cm)		Contractor cost: £55-£60 ha^{-1} y^{-1}	http://www.naac.co.uk/userfiles/files/contracting%20charges%202014-15.pdf http://www.fwi.co.uk/machinery/reducing-grassland-compaction-with-subsoiling.htm
Twose Grassland subsoil	3 leg subsoil C/W flat roll and front discs	£5,550		http://www.ellismachinery.co.uk/machinery/subsoilers

Technology	Short description	Capital cost	Annual costs	Reference
Cousins 7 Leg 4.5M V-Form	Cousins 7 Leg 4.5M V-Form (8554), second-hand machine	£13,000		http://www.ellismachinery.co.uk/machinery/subsoilers
Paraplough	Howard paraplugh 4 Leg (7594)2	£2,050		http://www.ellismachinery.co.uk/machinery/subsoilers

A1.7.4 Issues around implementation, current uptake

Soil-soiling is likely to be carried out by contractors as it is specialised equipment. There is increasing interest in sub-soiling. Data are hardly available on current extent of compaction, compaction risk, and subsoiling activities. According to a survey in Egnland, in 2012, on 51%, 43% and 20% of farms reported problems respectively of topsoil, plough depth and whole soil profile compacted (Defra 2013). A grassland survey in England showed that 16% of the soils were compacted (ADAS 2012). No Scottish data were found on the topic.

A1.7.5 Environmental co- effects

Reducing compaction will also reduce the likelihood of the preferential flow of pollutants to water course (Etana *et al.* 2013), and soil erosion. There is the potential for a reduction in soil compaction by applying precision farming techniques, and ensuring that the tyre pressures are at the correct setting. Avoiding applying fertilisers to the compacted tramlines will also reduce emissions. In the case of severe compaction, which is related to drainage problems, the equipment and infrastructure required is described in that section (Section A1.6).

A1.7.6 Recommendations for further work

There a wide range of estimates of the potential for a reduction in compaction to reduce emissions. The effectiveness will vary with soil type and the degree of compaction. Thus, a better understanding of the effectiveness of a reduction in compaction on GHG emissions and N leaching across a range of soil types would assist in determining its mitigation potential.

A1.8 Feed additives in total mixed rations

A1.8.1 GHG reduction mechanism

A range of feed additives have been incorporated into total mixed rations for ruminants with the objective to increase animal performance. Increasing performance generally reduces CH_4 emissions intensity (emissions per kg live weight gain or litre of milk). Probiotics (e. g. yeast products) are direct fed microbials that are fed to ruminants to increase productivity (Grainger and Beauchemin 2011). Yeast products have been used also to reduce the incidence of acidosis in cattle fed high levels of readily carbohydrates. Probiotics must be fed regularly (typically, daily) in order to maintain the effect and so are only applicable where animals receive supplementary feeding indoors, for example in parlour-fed concentrates or total mixed rations. Other additives with potential for GHG mitigation operate by directly inhibiting the methanogens and/or methanogenesis. There is a considerable body of evidence concerning the effects of addition of calcium nitrate (providing 1.5% nitrate in the whole diet) into ruminant diets. The toxicity of nitrate means that it needs to be introduced into diets gradually, under conditions of careful mixing and feeding of diets – in practice this means that it is only feasible when using total mixed rations. Other recent research (Haisan *et al.* 2014, Hristov *et al.* 2015, Reynolds *et al.*

2014) has identified 3-nitrooxypropanol as a potential CH_4 reducing additive; again it is likely that it would be incorporated into total mixed rations. Whilst we generally consider 'additives' to include compounds added at the sub-percent level, they merge into mitigation options based on altering the major diet ingredients. Perhaps the most successful anti-methane strategy is the use of high fat diets. High fat diets, particularly those containing high levels of unsaturated fatty acids, reduce enteric CH_4 emissions through a series of mechanisms – including a direct anti-methanogen effect, reducing the extent of fermentation in the rumen (displacing digestion to the intestines) and acting as an alternative hydrogen sink.

A1.8.2 Abatement rate

Table 13 Data from literature on abatement by probiotics

Abatement	Emission reduction	Country	Reference
Enteric CH_4	-7.5%	UK	(Moran *et al.* 2008) and (MacLeod *et al.* 2010b) based on (Moss *et al.* 2000) and (Van Nevel and Demeyer 1996)
Milk yield	+10%	UK	(Moran *et al.* 2008) and (MacLeod *et al.* 2010b) based on (Moss *et al.* 2000) and (Van Nevel and Demeyer 1996)
Milk yield	+2.7% (3.5% fat corrected milk)	various	(de Ondarza *et al.* 2010)
Enteric CH_4	-3% (95% confidence interval: -7% – +1%)	various	(Veneman 2014)

Table 14 Data from literature on abatement by nitrate

Abatement	Emission reduction	Country	Reference
Enteric CH_4	-20% reduction (95% confidence interval: -27% – -13%)	Various	(Veneman 2014)
Enteric CH_4	-2.1% to -46.5%	Denmark	(Petersen *et al.* 2015)
Enteric N_2O	Increase in N_2O emissions (usually <1% of N intake) usually negligible (<1% of CO_2e), but reduced GHG mitigation from -46.5 to -39.6% in the most extreme case	Denmark	(Petersen *et al.* 2015)

Table 15 Data from literature on abatement by 3-nitroxypropanol

Abatement	Emission reduction	Country	Reference
Enteric CH_4	-30% on g day^{-1} or g $(kg\ DM)^{-1}$ intake or g $(l\ milk)^{-1}$ basis	USA	(Hristov *et al.* 2015)
Enteric CH_4	-59% in CH_4 $(kg\ DM\ intake)^{-1}$; no effect on dry matter intake or milk yield	Canada	(Haisan *et al.* 2014)
Enteric CH_4	-6.6% and -9.8% respectively for doses of 0.5 and 2.5 g day^{-1}	UK	(Reynolds *et al.* 2014)

Table 16 Data from literature on abatement by high fat diet

Abatement	Emission reduction	Country	Reference
Enteric CH_4	Cattle: -4.16% per % fat on a DM basis Sheep: 8.11% reduction per % fat on a dry matter basis	Various	(Grainger and Beauchemin 2011)
Enteric CH_4	Dairy cattle: -3.88% per % fat on a DM basis Growing beef: -1.96% per % fat on a DM basis Sheep: -6.92% per % fat on a DM basis	Various	(McBride *et al.* 2015)
Enteric CH_4	Cattle: -4% (±0.8) per % fat on a DM basis	France	(Pellerin *et al.* 2013)

A1.8.3 Related technologies

Table 17 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Feed mixer	A mixer wagon is required to ensure that these additives are mixed thoroughly with the rest of the diet – this is variously important to ensure efficacy and reduce health problems	£15,000 – 40,000 depending on size appropriate for herd size	Software: up to £900 y^{-1}	
Feed storage space	Additives such as probiotics and salts are added at low levels and so require only small, clean/dry storage spaces. The use of novel feeds, such as oilseeds requires additional dedicated storage space that meets the standards for feed storage.	Feed storage space costs £200 m^{-2} (steel framed building, concrete walls and floor)		(SAC 2014) Building costs: (Steelfconstruction.info 2016)

A1.8.4 Issues around implementation, current uptake

Suppliers of feed mixers typically provide technical support, both for ration development and for maintenance and repairs of their feeders. There will be ongoing costs for this provision – service/maintenance; nutrition support linked to Cloud-based data capture from one of the leading mixer wagons is priced at £900 per annum.

Nitrate in particular has known potential adverse effects on animal health, and can lead to death through nitrate toxicity. Whilst this can be managed through gradual introduction into the diet, allied to careful mixing and monitoring of feeds, it is a major factor restricting uptake.

Issues around feeding stuffs regulations will need to be addressed in the case of materials that are not currently used or recognised as livestock feeds. This may involve a cycle of studies to confirm efficacy and safety for regulatory purposes.

High levels of fat supplementation can have serious adverse consequences for the fermentation activity of the rumen – so there is a delicate balance to achieve between CH_4 mitigation and achieving good rumen function and animal performance. It is generally recommended to keep total fat content below 6-7% of dry matter – placing a limit on the scope for CH_4 mitigation by this route. Mixing of diet ingredients is less critical for efficacy and animal health in the case of fat supplementation – though fat supplements and high-fat ingredients (e.g. full-fat or partially extracted oilseeds) are still most appropriate for a total mixed ration situation. Incorporation of high levels of oil into concentrates is an alternative option, particularly for dairy cows. Feeds that contain higher levels of oil cannot be stored for as long as feeds such as cereals, owing to their tendency to go rancid.

Currently in Scotland probiotics are not used as a daily feed additive (Eory *et al.* 2015). Nitrate and 3-nitrooxypropanol are not fed to cattle either. Regarding fats, high-productivity cattle are increasingly fed with an increased fat content diet though the fat content of those diets might still be lower than the recommended 5% (Eory *et al.* 2015). In 2014 in England 20% of livestock holdings increased the fat content of the diet (though the % fat content was not reported) (Defra 2015).

According to expert opinion, animals in most medium-large dairy herds (> 80 cows) already receive total mixed ration, while approximately 20% of the beef animals are fed total mixed rations (Eory *et al.* 2015).

A1.8.5 Environmental co- effects

Some of the additives lead to increased digestibility of feed, with consequent improvement in feed conversion efficiency and reductions in GHG emissions per unit milk or meat produced.

A1.8.6 Recommendations for further work

Research is suggested to identify strategies or co-additives that would remove the risk of nitrate toxicity (for example, through exploring interactions with rumen sulphate metabolism). Whilst 3-nitrooxypropanol was highly effective in two studies, the effect was much smaller (though nonetheless significant) in a third study – there is a need for more work to understand the large variability in methane mitigation effects.

A1.9 Precision feeding

A1.9.1 GHG reduction mechanism

Precision and multi-phase feeding are primarily directed at reducing the production of manure N from all classes of livestock – this results in reduced emissions of NH_3 and N_2O. Animal requirements for protein depend on age or weight and production level (growth rate or milk yield) and so precise feeding depends on the availability of information on each of these (i.e. regular recording of animal weights and or milk yields). Allied to this requirement is the need for regular analysis of feed composition – either per batch of supplementary feed or over the course of feeding out silages. There is a link between this topic and 'precision livestock farming' with the growing availability of technology for monitoring animals and feeds 'on farm'.

The large scale and detailed recording that is possible on large pig and poultry farms means that precision feeding and multi-phase feeding are already practised on many farms within Europe (JRC 2015). If individual animal records are not available, precision feeding could be implemented on a group basis – for example in 'phased feeding' in which pig diets are adjusted to take account of changing requirements as animals grow. Similarly, dairy farmers can offer different total mixed rations to groups of cows based on stage of lactation.

A1.9.2 Abatement rate

Table 18 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Manure NH_3 and N_2O	Low protein diets (sometimes allied to the use of specific amino acids) reduces N excretion: -5% – -60% for pigs, -10% – -35% for poultry -25% – -50% for cattle	various	(Agle *et al.* 2010, JRC 2015, Monteny and Erisman 1998, Rotz 2004)
Manure N_2O	Dairy cows: -70 – -124 kg CO_2e animal^{-1} y^{-1} Pigs: -276 – -692 kg CO_2e animal^{-1} y^{-1}	France	(Pellerin *et al.* 2013)

A1.9.3 Related technologies

Table 19 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Recording growth rates	Weighing crate – future developments will make the regular weighing of animals an automated process	Prices for weighers range from £1k to £10k depending on degree of automation		
Recording milk production	Automated milk yield recording system in parlour			
Feed analysis and nutrition models	Feed and consultancy companies provide a service of feed sampling and analysis, as well as ration formulation		Silage analysis by wet NIR costs £17; individual analyses cost £10-20 and full wet chemistry analysis could exceed £100 per sample	SAC Consulting Analytical Services Department Price List 2015/16
Feeding equipment	INDIVIDUAL: Equipment for individual feeding of animals – typical computer controlled concentrate feeders (in or out of parlour). GROUP: Feed mixer wagons are needed to implement a series of total mixed rations tailored to the nutrient requirements of groups of animals.	£15k - £40k depending on size appropriate for herd size	Maintenance and repairs: Software:up to £900 y^{-1}	

A1.9.4 Issues around implementation, current uptake

Farmers need access to feed analysis and nutrition modelling services – these are increasingly concentrated within feed companies – and there are some challenges to get independent advice if that is needed. See earlier comments (Section A1.8.4) on feed mixer wagons.

A1.9.5 Environmental co- effects

Great attention to detail and balanced diets have more general animal husbandry benefits, particularly in the area of health and welfare (reduced incidence of metabolic diseases; earlier detection of health problems). Balance diets improved the general health and fertility of dairy cattle in the analysis of Van de Haar & St-Pierre (2006).

Balancing the protein in the diets reduces all types of N emissions related to livestock husbandry, including NH3 emissions and nitrate and organic nitrogen leaching to waterbodies.

Production responses to dietary protein show a diminishing return to increasing levels. Previous practice tended to target higher levels than is strictly necessary in order to maximise output. Whilst recent work has tended to show little reduction in productivity through reduced protein feeding, it must always be borne in mind that we are dealing with a response surface, and that if levels fall too low there can be more marked negative effects on digestion, feed intake and performance.

A1.9.6 Recommendations for further work

Ration formulation models has not been a high priority for publicly-funded research in the UK in recent years – effort has been restricted to developments made by feed companies.

A1.10 Improved health monitoring and illness prevention: an example of Johne's disease

A1.10.1 GHG reduction mechanism

Johne's disease is estimated to be present in 71% of UK dairy herds, and affects approximately one in five dairy cattle (ADAS 2014, p88). It is estimated to be present in 44% of UK beef herds. For beef, the within-herd prevalence is unknown, but "is likely to be lower, due to generally smaller herd sizes" (ADAS 2014, p91). Johne's disease leads to adverse health effects which translate into higher emissions intensity (EI) of milk and meat production by cattle with the disease. The disease has the following impacts on dairy and beef cattle (ADAS 2014, pp 31, 32, 91): reduced growth rates leading to lower weaning and slaughter weights, reduced milk production, reduced cow fertility, increased risk of culling, increased cow replacement rate.

A1.10.2 Abatement rate

The total emissions, production and EI for a dairy herd with and without the measure were calculated in GLEAM (MacLeod *et al.* 2013), using the assumptions set out in Table 21. It is assumed that the measure decreases the within-herd prevalence by 75%, i.e. it decreases the proportion of infected cows from 20% to 5%. The results indicate that the measure would increase production by more than it would increase GHG emissions, leading to an overall reduction in the EI of the protein produced of 2.2%. If 61% of all dairy herds (i.e. 86% of those with Johne's prevalence) successfully implemented this measure (ADAS 2014, p8) the GHG emissions from Scottish dairy production could be reduced by 44 kt $CO_2e\ y^{-1}$, assuming constant production.

Table 20 Dairy herd assumptions used to calculate the impact of Johne's

Parameter	Change with Johne's 20% cows +ve	Notes
Milk yield	733kg lower per 305 day lactation for infected cows	(ADAS 2014, p91)
Growth rate	Infected calves 27.5kg lighter at weaning, i.e. growth rate reduced by ~10%	(ADAS 2014, p91)
Replacement rate (RR)	RR changed from 0.25 to 0.33, assuming that all cows with clinical symptoms are culled, but that max RR is 0.33.	
Fertility rate (FR)	Extension of calving interval by 43 days decreases FR from 0.92 to 0.82 for infected cows.	
Energy for immune response	Net energy requirement increased by 2% for infected cows.	(ADAS 2014, p184)
Waste	4 cows do not enter food chain (when 20% of cows in the herd are infected.	(Wright 2013, pp 31-32)
Feed conversion ratio	Johne's likely to increase FCR, but effect is uncertain, therefore FCR is constant in the model	

Table 21 Effect of treating Johne's on a dairy herd of 100 cows (modelled using GLEAM)

	Total emissions (kg CO_2e)	Meat and milk yield (kg protein)	EI (kg CO_2e (kg protein)$^{-1}$)		
			Meat and milk	Milk	Meat
Baseline 20% of cows Johne's +ve	2,199,678	32,053	68.6	65.7	94.1
Treatment 75% reduction in prevalence	2,207,373	32,888	67.1	62.7	104.0
Change with treatment	0.3%	2.6%	-2.2%	-4.6%	10.5%

Table 22 Estimated abatement potential from adoption of colostrum management and hygiene in the Scottish dairy herd in 2014, assuming constant production

		Source
Milk production (M l)	1,412	(Scottish Government 2015b)
GHG emissions from dairy herd – no treatment (kt CO_2e)	3,313	Calculated
Abatement potential (kt CO_2e y^{-1})	44	Calculated

A1.10.3 Related technologies

ADAS (2014, p171) identified three mitigation options for Johne's:

1. Colostrum management and hygiene;
2. Buying policy, test and cull; and
3. Vaccination.

Option 1 was estimated to have the biggest abatement potential for dairy cattle and can involve significant capital expenditure. The capital expenditure is required to adapt calving pens to make them easier to clean and to purchase equipment to pasteurise colostrum (Table 24).

Table 23 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Calving hygiene	More hygienic calving pens	£3,000 per calving area		(ADAS 2014, p171)
Colostrum management	Pasteurizer equipment	£6,000-£9,000		(ADAS 2014, p171)

A1.10.4 Issues around implementation, current uptake

There may be conflicts between this measure and the treatments used for calf pneumonia and diarrhoea (ADAS 2014, p171).

A1.10.5 Recommendations for further work

Further work is required to quantify the abatement potential in the beef sector in Scotland and to identify policy mechanisms to increase the uptake of the above mentioned measures. Future work should seek to capture the effect of increased FCR arising from Johne's, which could have a significant impact on emissions.

A1.11 Precision livestock farming

Whilst Precision Livestock Farming (PLF) encompasses monogastrics (pigs and poultry), this section will focus on ruminants (sheep, beef cattle and dairy cows).

A1.11.1 GHG reduction mechanism

Management practices, feeding schemes and pasture improvement can decrease GHG emissions on farms, even in extensive systems (Benoit and Laignel 2010). It applies advanced information and communication technology, targeted resource use and precise control of the production process (Banhazi *et al.* 2012). PLF has been defined recently, in a SRUC study, as "farming, using equipment, data or software which allows the use of information at a more individual level (animal, plant, field) for targeting decisions, inputs and treatments more precisely, with the aims including improving profitability, product quality, reducing environmental damage or having more efficient workloads" (Morgan-Davies *et al.* 2015a). PLF has the potential to improve ruminant management systems (more targeted input, less waste, better efficiency and production, better control of disease and production processes) and thus decrease GHG emissions or emission intensity.

A1.11.2 Abatement rate

Table 24 Data from literature on abatement by the mitigation option

Method	Emission reduction	Country	Reference
Targeted selective treatment to control worm burden in lambs: using Electronic Identification (EID) and lamb weight change in a bespoke algorithm	-10% per kg live weight gain	UK	(Kenyon *et al.* 2013)
Heat detection in cattle (e.g. Silent Herdsman, HeatWatch): sensors on the animal sending alerts to the farmer via a base station	Improved EI by reduced loss of milk production (if heat is missed, 3 weeks of milk production is lost)	UK; Ireland	(Gilroy et al 2016, Palmer *et al.* 2010), http://www.innovationforagriculture.org.uk/
Heat detection in sheep and goats	Improved EI by reduced loss of milk production, better synchronisation of artificial insemination and lactation peak (important for cheese making industry)	France	(Alhamada *et al.* 2016, Bocquier *et al.* 2014, Bocquier *et al.* 2006)
Targeted feeding systems for dairy cows: individual level concentrate supplementation	Improved EI by higher milk yield	Western Europe	(Andre *et al.* 2010)
Targeted feeding for sheep	Improved EI by better lamb survival	UK	(Jones *et al.* 2013, Wishart et al 2015)
Virtual fence: using a collar, a charger and a cable unit	Improved EI by more efficient pasture management	UK & France	(Joyce *et al.* 2013, Rutter 2014, Umstatter *et al.* 2015)

A1.11.3 Related technologies

There is a range of PLF options available for ruminant systems; however, not all of them are commercially available yet. The options range from management systems to use of specific software or equipment. The speed of development is increasing with greater sophistication and adaptability coming to the ruminant sector (especially sheep and beef cattle). Although little publications relate yet to GHG emissions, the improved efficiency demonstrated by using these technologies and equipment should transfer to reduced emissions intensity.

Table 25 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
EID for sheep	Tags (already compulsory)	£0.80 animal^{-1}		
EID for sheep	Tru-test readers. This works with the EID crate, and stores all information recorded (EID and weight, etc.)	£400-£1800 (excl VAT)		www.bordersoftware.com
EID for sheep	Handheld readers. These readers read the EID tags of the animals and the list can be downloaded onto a PC or send via Bluetooth onto a smart phone or tablet. The more sophisticated ones can stored additional information (e.g. lamb weight with EID tag)	£200-£800 (excl VAT)		www.bordersoftware.com, (Morgan-Davies and Wishart 2015)
EID for sheep	Farm software – with support	£300-£500 (excl VAT)	£60 (excl VAT)	www.bordersoftware.com
Weigh crate	Weighing and automatic sorting of sheep	£7,500 – £10,000		
Silent herdsman	Collars, base station and PC with the software	£85 per collar + £2,500 for base station, installation and training		www.silentherdsman.com
HeatWatch	Patch, base station, software	£3 per patch + £2,800-£3,500 for base station, monitor, repeater		www.cowchips.net
Robotic milking in dairy cow	Automatic milking system, with dynamic feeding related to the milk yield. Identification of animals with treatment	*circa* £70,000-£100,000		http://www.thedairysite.com/articles/2163/automatic-milking-how-effective-is-it/, SRUC Crichton farm cost of equipment
Virtual fence	Battery-powered receiver attached to a collar on animal, induction cable and a transformer	*circa* £210/collar + £350 for charger and cable unit		(Umstatter *et al.* 2015)

A1.11.4 Issues around implementation, current uptake

Although authors predict that PLF will revolutionise the livestock industry (Banhazi *et al.* 2012), the development and uptake of the technology is not uniform. In ruminants, the uptake is more prevalent in the dairy industry (e.g. milking robots, automatic feeders), but less so for the beef cattle and sheep industry. Costs, return on investment, lack of flexibility of the equipment, fear of the technology, lack of training and the amount of data generated are amongst the issues for the low uptake (Morgan-Davies and Lambe 2015, Morgan-Davies *et al.* 2015b).

A1.11.5 Environmental co- effects

In the future, a PLF approach should allow easier and better informed management. Positive welfare impacts have been debated (Wathes *et al.* 2008) and systems tailored around individual animals and their needs should offer better welfare protection. Labour savings (especially in areas where it is scarce) is a positive aspect to the technology. One drawback of PLF systems might be the risk of technology collapse due to environmental factors and extreme events (e.g. power cuts).

A1.11.6 Recommendations for further work

The existing research on PLF is quite patchy, with certain sectors (e.g. poultry, pigs and dairy cows) being more represented, and others distinctively lacking (e.g. sheep and beef cattle). More specific research into GHG emissions associated with the use of PLF for these latter sectors would be useful, especially given their use in the management of Scotland's dominant land cover type.

A1.12 Covering slurry stores and farm yard manure

A1.12.1 GHG reduction mechanism

GHG emissions from slurry tanks result mostly from indirect N_2O emissions associated with NH_3 loss. Covering a slurry store can significantly reduce the rate of NH_3 volatilisation. Slurry stores are also a point source for CH_4 emissions with emissions of 1.7 g CH_4-C m^{-2} h^{-1} having been reported (Sommer *et al.* 2000). However, slurry tank covers have relatively little effect on CH_4 emissions. Direct N_2O emissions from uncovered slurry stores are thought to be negligible (Chadwick *et al.* 2011).

A range of options for covering slurry tanks are available and this choice will affect both the cost and abatement rate of the approach. **Tents** are the simplest approach offering the opportunity to cover a slurry store with a flexible cover supported by a central pillar. This approach normally uses a conical structure in order to shed rainwater effectively. **Solid lids** can be supported by the tank walls, and these can be constructed from plastic, wood or concrete. Plastic and wood covers may be fitted retrospectively, however concrete lids can only be used where the structure is specifically designed to accommodate their weight. **Storage bags** are made of flexible impermeable material and placed within a tank allowing them to be filled with slurry. Options are available with a capacity of up to 5000 m^3. A range of options can be used to provide **floating covers** on slurry stores. These include floating plastic films, clay balls, and other materials. It is also possible to promote the development of **surface crusts** on slurry stores avoiding agitation. **Straw** can also be placed on the surface of slurry is a temporary cover, however the material will eventually sink within the slurry and can cause difficulty with pumping and transport of the slurry.

A1.12.2 Abatement rate

Baseline emissions of NH_3 from slurry tanks are variable, and depend upon prevailing weather conditions and the characteristics of the slurry. Reported emissions range from 0.8 kg NH_3 m^{-2} y^{-1} for crusted cattle slurry to 2.9 kg NH_3 m^{-2} y^{-1} for pig slurry (Misselbrook *et al.* 2000). The estimated abatement rates and costs for different slurry covers are indicated in Table 27 which is modified from a recent review (VanderZaag *et al.* 2015).

Table 26 Data from literature on abatement by the mitigation option (modified from VanderZaag et al. 2015)

Abatement	Cover type	Abatement	Cost (£ m^{-2} y^{-1})	Cost[a] (£ m^{-3} y^{-1})	Abatement cost[a] (£ kg NH_3-N^{-1})	Country	Reference
NH_3 from tank	Tent	80	7.07	2.02	3.05 - 6.32	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Lid (wood)	80	4.80	1.37	2.07 - 4.28	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Lid (concrete)	80	8.25	2.36	3.56 - 7.36	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Storage bag	80	17.21	4.92	7.44 - 7.44	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Floating impermeable, negative air pressure	80	4.09	1.17	1.76 - 5.69	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Floating permeable synthetic covers	60	1.40	0.40	0.81 - 2.61	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Hexacover	60	2.28	0.65	1.31 - 4.23	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Clay balls	65	2.96	0.84	1.57 - 5.05	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Straw[b]	50	1.25	0.36	0.86 - 2.78	various	(VanderZaag *et al.* 2015)
NH_3 from tank	Crust	40	0.00	0.00	0.00 - 0.00	various	(VanderZaag *et al.* 2015)

[a] data were converted between area and volume assuming a depth of 3.5 m for tanks, basins, and lagoons

[b] assuming two applications of straw per annually

A1.12.3 Related technologies

Slurry store covers can be impermeable or permeable, fixed (rigid) or floating. A central distinction in there design is if they can exclude or separate out rainfall. An important consideration is the design and condition of the store. Fixed cover options for tanks will cause additional structural stresses and require an engineering certificate and this increases costs. Floating covers are the least expensive and have no impact on the structure of the slurry store or lagoons. They can however introduce difficulties for slurry management requirements such as agitation and store cleaning. This problem can be overcome with new builds but for older tank this can difficult and adds extra cost. The use of aggregates is a relatively low cost option and is easy to install but has annual cost and no secondary benefits such as the exclusion of rainfall. Concrete, steel and wooden lids are not options for existing slurry stores as they would require extensive re-engineering.

Table 27 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Fixed covers	Purpose built PVC covers. Required bespoke design with costs varying widely	> £13,000		Cunningham Covers Ltd Stefos
Floating plastic plates	Free floating plastic plates	£20 – £40 m^{-2}		Commercial Sales
Plastic membranes	A fixed or free floating plastic sheet	£1 – £25 m^{-2}	Electricity for water pump	Commercial Sales
Lightweight expanded clay	100 – 150 mm layers that floats on surface	*circa* £15 m^{-2}	£500	Specialist Aggregates

Technology	Short description	Capital cost	Annual costs	Reference
Integral store	A purpose build reinforced bag	*circa* £30 – £40 m^{-3}		Albers Alligator, DairyCo

A1.12.4 Issues around implementation, current uptake

A recent analysis by DEFRA reported that 28% and 2% of holdings have covered slurry tank and lagoon facilities, respectively (Defra 2015). The main barriers to uptake are considered to be costs of installation.

Additionally, there are health and safety concerns in regards to reducing gas emissions. Slurry gas is highly toxic and the retention of additional gases within the liquid volume will increase this risk.

For existing stores there are engineering considerations for some of the storage options that can raise costs. Permeable covers do not allow rainwater to be separated out which is a major benefit of covers. This option would likely only be considered by those with other issues that must be addressed such as odour control.

A1.12.5 Environmental co- effects

The main benefits of covering slurry stores are associated with reductions in NH_3 emissions, and associated indirect emissions of N_2O. Additional benefits include reduced nutrient loss and reduced dilution of the slurry by rainwater (therefore reducing fuel use associated with spreading), and reduced odour.

A1.12.6 Recommendations for further work

There is a need for the improved understanding of the integrated benefits of slurry covers and potential barriers to uptake.

A1.13 Slurry acidification

A1.13.1 GHG reduction mechanism

With commercially available technologies, slurry acidification is achieved by adding strong acids (e.g. sulfuric acid or hydrogen chloride) to the slurry to achieve a pH of 4.5-6.8 depending on the slurry type, the acid used (Fangueiro *et al.* 2015). The CH_4 and also the NH_3 emissions (therefore the indirect N_2O emissions) are markedly reduced in an acidic environment. The effectiveness of acidification will be higher if implemented early in the manure management chain.

A1.13.2 Abatement rate

Table 28 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Manure CH_4	-67 – -87% with sulphuric acid -90% with lactic acid -40 – -65% with hydrochloric acid -17 – -75% with nitric acid	Various	(Fangueiro *et al.* 2015)
Manure NH_3	-50 – -88% with sulphuric acid -27 – -98% with other acids	Various	(Fangueiro *et al.* 2015)

Abatement	Emission reduction	Country	Reference
Soil N_2O from manure spreading	+23%	Various	(Fangueiro *et al.* 2015)
Manure NH_3	-95 – -99%	Denmark	(Petersen *et al.* 2012)
Manure and housing NH_3	-44 – -71% (uncertain results due to low emission levels)	Denmark	(Petersen *et al.* 2016)

A1.13.3 Related technologies

There are three main types of technology relating to the stage at which the acid is added to the slurry: in-house, in the storage tank, or before field application (Fangueiro *et al.* 2015).

Table 29 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
In-house acidification	The slurry is pumped out to an outside process tank where it is mixed with a strong acid to reach pH 5.5; then most of the slurry is pumped back to the house so that fresh slurry to be mixed with acidified slurry right after excretion. The excess acidified slurry is transferred to a storage tank. This technology enables the slurry to be acidified right after excretion, but requires a modification not only in the storage unit but in the housing as well.			(Petersen *et al.* 2016, see Supplementary Information)
		£70,000 for 267 livestock unit dairy cattle	£4,500 y^{-1} (without depreciation or interest)	Petersen *written comm.*, based on an economic assessment made for a Danish farm
		Annualised cost: £43 (500 kg livestock unit)$^{-1}$		(Kai *et al.* 2008)
Storage tank acidification	The acid is added to and mixed with the slurry in the slurry tank, either at regular intervals as the tank is being filled up, or shortly before field application. In the latter case the overall emission reduction is lower. An acid-proof storage tank and the automatic mixing system needs to be installed. Lower investment is required, but emissions from the livestock housing are not reduced.			(Fangueiro *et al.* 2015)
		£9,000 (slurry tank mixer is not included; it might be available on the farm)	£4,500 y^{-1} (assuming similar annual costs as to in-house acidification)	Petersen *written comm.*, based on an economic assessment made for a Danish farm

Technology	Short description	Capital cost	Annual costs	Reference
		For 60,000 t manure (~6,000 dairy cows, housed 42% of the year): £52,000 y^{-1}	Mainteance, time: £5,000 y^{-1} Acid: £34,000 y^{-1}	(Hansen *et al.* 2013)
Acidification at field application	The acidification takes place in when the slurry is pumped into the slurry spreader. Acidification at this stage affects only NH_3 emissions and hence N use efficiency and N_2O emissions, but not CH_4 emissions.	For 60,000 t manure (~6,000 dairy cows, housed 42% of the year): £51,000 y^{-1}	Mainteance, time: £400 y^{-1} Acid: £76,000 y^{-1}	(Fangueiro *et al.* 2015) Cost data: (Hansen *et al.* 2013)
All types of acidification			Cost of acid: £0.2 – £0.4kg^{-1}	Petersen *written comm.*

The cost of implementing a measure is £2.40 (t slurry)$^{-1}$, according to the Baltic Deal farmers' organisation (Baltic Deal 2015). With annual slurry production of 0.35, 0.2 and 0.03 t for dairy, beef and pigs this translates to £44, £25 and £4 head^{-1} y^{-1}, respectively. Kai *et al.* (2008) provided a cost estimate of £43 y^{-1} for a 500 kg livestock unit.

On the benefit side, the reduced N loss can increase the N content of the slurry, increasing the mineral fertiliser equivalent value of the manure by 39-100% (Fangueiro *et al.* 2015), thus reducing the need for additional synthetic N fertilisation. These savings in synthetic N equivalent were reported to be 26 kg N (100 kg slurry N)$^{-1}$ (Kai *et al.* 2008).

A1.13.4 Issues around implementation, current uptake

Currently this mitigation option is commonly used in some European countries (e.g. in Denmark), but not applied in Scotland or in other parts of the UK.

This technique is applicable to slurry which is stored in tanks, regardless of the livestock type. For dairy, beef and pig excreta, 41%, 4% and 38% respectively is stored in liquid form (Webb *et al.* 2014), in England half of this is stored in slurry tanks as opposed to slurry lagoons (Defra 2014). Therefore the applicability of the measure is 21%, 2% and 19% for dairy cattle, beef cattle and pigs.

The uptake of the measure might be hindered by the risks posed by handling the strong acids. On the benefit side, the acidity of slurry means that NH_3 emission from application is very low even without using specific low emission slurry spreading equipment (Christensen and Sommer 2013).

A1.13.5 Environmental co- effects

Slurry acidification can efficiently and significantly reduce NH_3 emissions from the stored and applied slurry. However, the odour of the acidified slurry might be worse than of the non-acidified slurry, and higher leaching losses might occur after spreading (Fangueiro *et al.* 2015).

A1.13.6 Recommendations for further work

As the concept is novel in Scotland, a well-planned extension and advisory work is desirable. Further technological development regarding the use of concentrated acids could lead to faster uptake of the measure once it's introduced to Scotland. Longer term research might lead to the development of equipment for the acidification of solid manures.

A1.14 In-house poultry manure drying

A1.14.1 GHG reduction mechanism

In poultry houses the microbial degradation excreta results in substantial NH_3 emissions. Beyond being a significant atmospheric pollutant in itself (acidification, eutrophication) NH_3 (also in the form of NH_4^+) has an indirect effect on climate change both in the form of indirect N_2O emissions and via NH_4^+ aerosols promoting cloud formation.

The amount of NH_3 that is emitted to the atmosphere depends, among other factors, on the internal concentration of the gas, the ventilation rate, and the temperature. Frequent removal of the manure to an outside storage area and drying of the manure can significantly reduce NH_3 emissions. Broiler litter should have a dry matter content of 60% -70% and layer manure a dry matter content of >50%. The rate of drying is important as the objective is to rapidly create conditions in the manure that are not conducive for microbial degradation of uric acid and undigested proteins.

For layer systems using manure collection on belts, emissions can be reduced by frequent emptying of the belts i.e. twice per week, or less frequent emptying of the belts (once per week) if there is forced air drying of manure. With littered floor systems such as those commonly used for poultry meat production, dry friable litter is maintained by good insulation of the house to maintain the desired humidity and by optimising the ventilation.

A1.14.2 Abatement rate

Table 30 Data from literature on abatement by the mitigation option

Abatement	NH_3 emission reduction	Country	Reference
Manure NH_3	Frequent removal (twice per week to closed storage): 54-58%	Denmark	(JRC 2015)
Manure NH_3	Manure belts and forced air drying: 58%	NL	(JRC 2015)
Manure NH_3	Improved forced air drying (drying tunnel): 70-88%	NL	(JRC 2015)

A1.14.3 Related technologies

Systems for drying manure in layer housing are readily available on the market and are usually designed into new buildings. It can be costly to retrofit air drying systems into older housing as often the whole production system has to be renewed. Manure drying can also be achieved by the use of underfloor heating. Most new broiler units are now built with underfloor heating and biomass boilers.

Table 31 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Manure removal and drying on belts (enriched cage)	Manure is collected on a conveyor belt located below enriched cages in the house. Belts are usually emptied once or twice a week	£8-12 (bird place)$^{-1}$		(JRC 2015)
Manure removal and drying on belts (aviary system)	Manure is collected and dried on belts located below perches in the house. Belts are emptied once or twice a week.	£10-13 (bird place)$^{-1}$	£1.80-2 (bird place)$^{-1}$	(JRC 2015)

A1.14.4 Issues around implementation, current uptake

Large, intensive poultry units (above 40,000 bird places) have to comply with the Pollution Prevention and Control (Scotland) Regulations 2000, which require the poultry houses to either remove manure twice a week or, if manure is removed once a week, apply forced air drying (Anon. 2013). Additionally, the majority of enriched cage houses for laying hens have systems for frequent manure removal and in many cases air drying of manure on belts is also available. As cages systems have to be upgraded to enriched cage houses when the Welfare of Laying Hens Directive (1999/74/EC) came into force in 2012, most of cage houses have low-emission technologies installed. Furthermore, newer aviary free range houses also have manure belt systems with options for frequent removal and forced air drying. Statistics exist for the England and Wales on the housing system and the existence of belts (Defra 2006, Defra 2010), though not on the manure drying procedures followed. According to these statistics 9% of broilers and 44% of laying hens were in free range systems, 91% and 0.1% of them, respectively, on deep litter. 49% of laying hens were in cages, of which half were in deep pit or stilt houses (manure collected underneath the cages) and half in houses with a manure belt or manure scraper. However, given recent changes in poultry housing the expert opinion is that almost all caged laying hens are in improved cages with a manure belt or manure scraper.

However, there are a number of older systems (particularly on farms not covered by these regulations) that could benefit from upgrading.

A1.14.5 Environmental co- effects

As well as reducing NH_3 emissions, techniques such as air drying of manure will also help to reduce odour emissions. Odours are an increasingly important issue in more populated rural environments. Additionally, bird health and performance is improved because of the lower NH_3 levels.

A1.14.6 Recommendations for further work

The current UK NH_3 emission inventory is unlikely to reflect the recent significant improvement in poultry housing and consequent reduction in NH_3 emissions that has resulted from legislative drivers such as the Welfare of Laying Hens Directive and the Pollution Prevention and Control permitting regime. Work is needed to establish an up to date inventory that reflects current best practice.

A1.15 Low emission livestock housing

A1.15.1 GHG reduction mechanism

A range of technologies and building design (e.g. floor design, ventilation and in-house manure management) exist to reduce gaseous emissions from livestock buildings. Most of these solutions are aimed for reducing manure-related NH_3 and GHG (CH_4 and N_2O) emissions and energy use. Research and polices have been focusing on the pig and poultry sectors where many animals are housed all-year-round. As ruminant animals on average spend a much lower proportion of the time housed, and because no feasible end-of-pipe technologies exist at the moment to reduce enteric CH_4 emissions (the most important GHG emissions from ruminant housing), options for reduced GHG emissions from ruminant housing are less available.

Housing systems can be designed to reduce the NH_3 emissions by minimising the surface area covered with urine, reducing the temperature of these areas and/or the stored manure, reducing the pH and/or temperature of the manure, reducing the air flow above the manure, drying poultry manure, and treating the exhaust air using acid scrubbers. Mitigating NH_3 emissions reduces the related indirect N_2O emissions, and some of these solutions also reduce CH_4 emissions (reducing the pH and temperature of manure). In-house climate control design and improvements in other energy intensive processes (e.g. milking) can reduce energy use and the related CO_2 emissions. Part of these opportunities are discussed in other sections of the report: slurry acidification in Section A1.13, in-house poultry manure drying in Section A1.14, energy efficient heating and ventilation in Section A1.18 and energy efficient milking and milk handling in Section A1.20.

A1.15.1 Abatement rate

The reduction in NH_3 and GHG emissions achievable highly depend on the specifics of the old and the new (or retrofitted) housing system and on the livestock considered (e.g. lactating sows or fattening pigs). The capital and maintenance costs of the new building(s) are also highly variable. One example for the range of costs and estimated reductions in NH_3 emissions is a Spanish case study for pig housing by Montalvo *et al.* (2015), presented in Table 31.

Table 32 Data from literature on abatement by the mitigation option (adapted from Montalvo et al. 2015)

Growing phase	Technology	New built or retrofit	Extra cost (£ pig place^{-1})	Reduction in NH_3 emissions (%)
Gestating sows	Partial slat and reduced pit	New built	5.68	35
		Retrofit	6.83	35
	Littered system	New built	47.67-55.41	14
		Retrofit	72.72-80.46	14
	Frequent manure removal	NA	0.00	25
Lactating sows	Combination water-manure channel	New built	3.29-3.95	52
		Retrofit	16.74-20.09	52
	Manure pan underneath	New built	17.52-21.04	32
		Retrofit	30.98-37.18	32
Weaners	Manure channel with sloped floor	New built	0.00-0.23	60
		Retrofit	1.28-2.67	60
	Partial slat	New built	0.00	25
		Retrofit	0.88-2.25	25

Growing phase	Technology	New built or retrofit	Extra cost (£ pig place^{-1})	Reduction in NH_3 emissions (%)
	Frequent manure removal	NA	0.00	25
Growers-finishers	Partial slat	New built	0.00	30
		Retrofit	3.61-4.33	30
	Littered system	New built	25.72	20
		Retrofit	42.07	20
	Manure channel with sloped floor	New built	0.73	10
		Retrofit	6.45	10
	Frequent manure removal	NA	0.00	30

A1.15.2 Related technologies

Some examples of related technologies for pig housing are presented in Table 31, with some further technologies detailed in other sections of the report.

A1.15.3 Issues around implementation, current uptake

Large, intensive pig and poultry units (above 40,000 bird places, 2,000 production pig places or 750 sow places) have to comply with the Pollution Prevention and Control (Scotland) Regulations 2000, require the implementation of Best Available Techniques on farms. These techniques are mostly aimed for reducing NH_3 and odour emissions. Additionally, animal welfare regulations covering the laying hen sector also required upgrading the livestock buildings, often with a positive impact on NH_3 emission mitigation (see Section A1.14.4). Some relevant pig and poultry housing statistics are available for England and Wales (Defra 2006, Defra 2010), though not for Scotland.

A1.15.4 Environmental co- effects

The most important environmental benefits of new housing systems are reduced NH_3 and odour emissions. The improved manure storage can also lead to reduced N leaching. Additionally, new building design allows better consideration of animal welfare issues.

A1.15.5 Recommendations for further work

Given the scarce data on the costs of housing improvements and new houses a compilation of recent case studies would be desirable, along with statistics on housing systems and manure handling procedures in Scotland. The ruminant sector has been less in focus for low emissions building design. A review of available options and statistics of current practice can fill this gap.

A1.16 Anaerobic digestion

A1.16.1 GHG reduction mechanism

Biogas is produced when bacteria break down organic matter in an atmosphere with little or no oxygen. This will occur anywhere that there is decomposition, including in the soil. It also occurs in slurry stores. The gases from this process, predominantly CH_4 and CO_2 are then released into the atmosphere. However, anaerobic digestion follows the same principles, which occur naturally in a controlled environment where by the gases can be collected and used.

Biogas comprises of about 60% CH_4 and 35% CO_2 with other gases making up the rest including H_2S. These gases are normally released out into the atmosphere when plants and slurries decompose, however, using an anaerobic digestion (AD) plant captures these gases to produce energy, which can be used for heating and electricity. In some cases the biogas can be cleaned and used for road fuel or mains gas.

For livestock slurry feedstocks GHG emissions will result from storage and spreading of the digestate, and from leakage from the digester. GHG savings will result from avoided heat and electricity, avoided losses from raw slurry storage and application, and by avoidance of inorganic fertilisers. Where energy crops are used the savings in GHG emissions will depend on the specific inputs and yields associated with each crop. Sustainability requirements introduced to the Renewable Heat Incentive (RHI) scheme in October 2015 require that emissions savings must provide a 60% saving over EU fossil fuel heat average (Ofgem 2015).

A1.16.2 Abatement rate

Table 33 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Manure CH_4 and avoided CO_2 from replaced energy production	1.5 t CO_2e (t dry matter)$^{-1}$	UK	(Mesa-Dominguez *et al.* 2015)
Manure CH_4 and avoided CO_2 from replaced energy production	0.1 t CO_2e (fresh biomass or waste t)$^{-1}$ (agricultural AD)	UK	(Mistry *et al.* 2011, Table 15)
Manure N_2O and CH_4 and avoided CO_2 from replaced energy production	0.55, 1.56 and 0.37 t CO_2e animal^{-1} y^{-1} for dairy cows with solid manure storage, dairy cows with liquid manure storage and fattening pigs (>50 kg) with liquid manure storage (equivalent to 0.06 – 0.16 t CO_2e (fresh manure t)$^{-1}$)	France	(Pellerin *et al.* 2013)
Manure CH_4 and avoided CO_2 from replaced energy production	Cattle manure and maize silage, 250 kW: 0.36 t CO_2e (fresh manure and biomass t)$^{-1}$) Pig/poultry manure and maize silage, 500 kW: 0.89 t CO_2e (fresh manure and biomass t)$^{-1}$) Maize silage only, 1000 kW: 1.49 t CO_2e (fresh biomass t)$^{-1}$)	UK	(Eory *et al.* 2015)

A1.16.3 Related technologies

Table 34 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Anaerobic digester	Typical farm scale combined heat and power (CHP) anaerobic digester using slurry, farm yard manure and energy crop feedstocks, with an allowance for additional fodder, digestate storage and grid connection	£1.5m for 250 kWe £3.9m for 1 MWe	£110,000 for 250 kW £250,000 for 1 MW (excluding crop production costs)	Supplier quotes and SAC consultancy projects
Anaerobic digester	$Capital\ cost\ (£) = 79.5 * Substrate\ (fresh\ t\ y^{-1})\ + 516{,}000$ $Opreational\ cost\ (£\ y^{-1}) = 218 * Capacity\ (fresh\ t\ y^{-1})^{-0.306}$			(Mistry *et al.* 2011)

A1.16.4 Issues around implementation, current uptake

- Slurry only AD plants would allow mainstream farming activities to continue as normal, therefore are attractive to farmers. They also offer considerable GHG abatement potential.
- Financial viability of farm scale AD plants currently requires the use of high energy value feedstocks in order to generate sufficient revenue to justify the capital expense. Continuity of supply of these feedstocks can be difficult to assure with imported feedstocks, therefore energy crops often provide the most reliable source.
- Land and crop availability for timely distribution of digestate can be a problem particularly where imported feedstocks are used. Possible land contamination from digestate derived from imported feedstocks has to be considered.
- Efficient use of heat from a CHP system is important to maximise benefits (financial and carbon). Matching seasonal heat demands to CHP output can be difficult.
- Availability and cost of electricity and/or gas grid connections is problematic for many potential plants.
- Public perception of AD plants can result in planning difficulties.
- Low conventional crop prices have seen an increased interest in AD. Conversely the long term commitment required has dissuaded some farmers who fear "lost opportunity" should conventional crop prices rebound.

A1.16.5 Environmental co- effects

There is a potential odour reduction within livestock farms where digestate is spread in place of raw slurry. Reduction of reliance on fossil fuels and the volatility of oil prices can reduce costs for farm businesses and improve budgeting. The "green" credentials of farm produce can provide a marketing advantage. Introduction of energy crops to crop rotations can spread demand on labour and equipment.

A1.16.6 Recommendations for further work

As AD plants become more popular the demand for small scale plants on dairy farms to help abate the GHG should be a focus. Currently the cost of the plants are too high to make it viable, however, the overall benefits of abating GHG emissions could have a significant effect. Moving forward small scale AD should be a key focus to improve financial viability and environmental sustainability.

Biogas as a fuel for farm vehicles would provide further GHG savings. Biogas tractors are currently produced by one European manufacturer although these currently require gas grid quality biogas which would be expensive to produce at a small scale. Further development of this technology is worthy of deeper investigation.

A1.17 Capital investment in fuel efficiency

A1.17.1 GHG reduction mechanism

Fuel efficiency improvements can be achieved by many different means. Some of these, such as the adoption of precision agriculture or minimal tillage techniques, are covered elsewhere in this document and are not therefore covered here. Savings associated by improved diesel engine technology are covered by European legislation and will be mandatory on new vehicles and do not therefore need financial incentives. Other vehicle technology such as engine stop/start as fitted to many modern cars or closed centre tractor hydraulics also have the ability to reduce emissions but are not easily retro-fitted to existing vehicles and do not represent a significant or definable portion of the cost of a new vehicles and would therefore be difficult to subsidise. Further savings could be gained from changes to driver habits and management practices, but again these cannot be described as capital investments and therefore do not fit here (see more details on this option in Frelih-Larsen *et al.* (2014) and Eory *et al.* (2015)).

Energy independent farming is a concept that has potential to reduce GHG emissions from agriculture. Where farmers have invested in renewable generation technology there is an opportunity to make better use of the renewable energy on site and offset the use of fossil fuels. Several technologies are available which would currently facilitate this and others are in development. Changing farm vehicles to renewable energy sources is currently an option in a limited number of cases and the range of these options is increasing. To ensure the benefit from any change it will be necessary to ensure that continued use of the renewable energy source is ensured through the life of the vehicles. Industrial type lift trucks as used in on-farm potato stores and quad bike ATVs are two vehicle types that are currently available as electric powered variants.

A1.17.2 Abatement rate

Table 35 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Fuel CO_2	Replace fossil fuelled lift trucks with electric trucks charged from renewable sources: 6.7 t CO_2 (1000 hours operation)$^{-1}$		Based on diesel yard/store truck with fuel consumption of 2.5 l hr^{-1}
Fuel CO_2	Replace fossil fuel quad bike with electric quad bike: 75 kg CO_2 (1000 miles)$^{-1}$		Based on petrol quad bike with fuel consumption of 40 mpg

A1.17.3 Related technologies

Table 36 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Electric lift trucks	Battery powered warehouse type lift truck	*circa* £20,000		Review of company information for 3 to 4 tonne electric trucks
Electric quad bike	Battery powered farm quad bike	£8,995		http://ecochargerquads.com/

A1.17.4 Issues around the implementation of the mitigation option, current uptake

A limited range of hydrogen powered lift trucks and other vehicles are also available or in development and will provide an alternative option for zero carbon vehicles provided that the hydrogen is produced from renewable energy. Development of hydrogen production facilities at a farm level and associated supply chain would be necessary before this technology could be fully deployed.

A1.17.5 Environmental co- effects

Fuel efficiency needs to be considered along with other GHG reduction effects when looking at cultivation, crop establishment, fertiliser spreading and harvesting techniques which are covered under precision farming. Savings will be brought about by changes to an overall system of working and it is therefore difficult to identify capital items to invest in under a heading of fuel efficiency which will deliver GHG savings.

A1.18 Energy efficient heating and ventilation of livestock buildings

A1.18.1 GHG reduction mechanism

The main GHG reduction mechanism associated with efficient heating and ventilation of livestock buildings is probably that associated with reduced consumption of fossil fuels to power heating and ventilation systems. Buildings that require heating should be adequately insulated to reduce heat loss and mechanical ventilation systems should be designed using low energy fans to efficiently change the air required for optimum livestock welfare. Sophisticated control systems will further reduce energy consumption of fans. For some livestock in some climatic locations automatically controlled naturally ventilated buildings may be used to remove the need for mechanical ventilation completely.

GHG reductions can also be achieved by selecting renewable sources of fuel for heating systems such as wood-fuelled boilers, or using renewable electricity sources to power mechanical ventilation systems. Greater efficiencies can be achieved by recovering warm exhaust air and using it to heat cold incoming air via the use of heat exchangers.

Various renewable technologies exist which can provide efficient and clean ways of heating: heat pumps (air to air, air to water and ground source), biomass boilers, solar thermal. Some of these can also provide cooling. These technologies tend to have high upfront capital costs but relatively low running costs. The use of a CHP in conjunction with a biomass boiler or AD plant would have the benefit of providing electricity as well as heat.

A1.18.2 Abatement rate

Table 37 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Energy CO_2	Maximising the benefits of natural ventilation by building design: Energy consumption -60%	UK	(Carbon Trust 2012, Ecim-Djuric and Topisirovic 2010)
Energy CO_2	Onsite renewables for heating, cooling and powering ventilation: GHG saving of -339 g CO_2 kWh^{-1} (based on average grid carbon intensity 15/02/2016)	UK	http://www.earth.org.uk/_gridCarbonIntensityGB.html
Energy CO_2	Ground source heat pumps for chicken shed: -57.2% energy demand	Syria	(Kharseh and Nordell 2011)
Energy CO_2	Improved insulation: -15% energy consumption	UK	(Carbon Trust 2012)
Energy CO_2	Heat recovery systems: capturing excess heat from either the building itself or the boiler/heating equipment for use elsewhere. Air to air heat exchangers in poultry houses: -40% liquefied petroleum gas consumption	Syria	(Kharseh and Nordell 2011)
Energy CO_2	Air to air heat exchangers in poultry houses: -38% gas use	NL	(Bokkers *et al.* 2010)
Energy CO_2	High efficiency boilers/heaters (pigs and poultry) Bio-mass boilers fuelled by renewable sources such as wood pellets or poultry litter	EU	(JRC 2015)
Energy CO_2	Automatic control of ventilations systems: -45% electricity usage	Israel	(Teitel *et al.* 2008)

A1.18.3 Related technologies

Table 38 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Variable-speed drives	Controls the speed fans operate at, ensures they are not working at 100% all of the time if it is not required. Costs vary depending on required size, connected straight to motors electricity supply. Care need to be applied with the use of variable speed fans as the dispersion characteristics of pollutants in the atmosphere may be poorer.	Varies depending on required scale, typically £200 to £1000	NA	(Carbon Trust 2012, Teitel *et al.* 2008), prices from Google search
Energy efficient fans	Select fans with low energy consumption per m^3 of air. Operate fans efficiently e.g. one fan at full capacity is more efficient than two fans operating at half capacity	Information not available	Low	(JRC 2015)
Automatic control of natural ventilation shutters	Controls when ventilation takes place to maximise benefit and savings based on climatic conditions. Reduces heat waste.	Information not available	Low	(Carbon Trust 2012)
Radiant heating	Mounted overhead, directly heats solid objects/animals providing more efficient and effective heating than space heating systems.	Information not available	Low	(Carbon Trust 2012)
Biomass boiler	Installation of a biomass boiler. Has large upfront capital costs and long term running costs associated with fuel but can be offset by eligibility for RHI payments.	10-20kW system: £945 kW^{-1}, 20-50kW system: £568 kW^{-1}	Fuel for boiler and maintenance costs (approx. £0.05 kWh^{-1})	(DECC 2013)
Heat exchanger	Captures waste heat to be used elsewhere.	Information not available	Low	http://www.uk-exchangers.com/
Insulation	Insulating pipes, buildings and roofs to improve energy efficiency.	Information not available	NA	(Carbon Trust 2012)

A1.18.4 Issues around implementation, current uptake

- Natural ventilation may not be a suitable option when external temperatures get too high, therefore some other method would likely be required also.
- Long term contracts may be required for maintenance of technologies and for providing fuel for biomass boilers.
- For heat exchangers not all of the heat will necessarily be at a useful temperature.
- Savings are likely to be very site specific, and some buildings might be unsuitable for some technologies.
- RHI and Feed-in Tariff currently promote the uptake of renewable technologies through government policies but the continued long term financial support under these schemes is unclear.

- Business need to maximise RHI income may be a disincentive for some energy saving technology such as heat exchangers.

A1.18.5 Environmental co- effects

Optimum heating and ventilation of livestock buildings will have the benefit of providing good welfare conditions for livestock helping to ensure that feeding regimes are optimised thus reducing emissions of, for example, methane and ammonia at source. Optimum conditions can result in healthier animals and higher yields.

Whilst heat exchangers will also have an energy requirement there can be additional benefits in some systems such as reduced dust and NH_3 emissions. Improved ventilation systems will also reduce dust and moisture.

Further operational reductions in emission can be obtained in some systems by using warm exhaust ventilation air to rapidly dry manure thus reducing ammonia emissions.

A1.19 Energy efficient crop drying

A1.19.1 GHG reduction mechanism

Removing moisture from grain in a timely fashion in order to prevent spoilage but without causing damage to the grain in the drying process is paramount to achieve a high quality product. Greater efficiencies in the drying operation and hence a reduction in the GHG emissions related to drying operations can be achieved by:

- Replacing fossil fuel heat sources with renewable technology such as biomass.
- Replacing older inefficient fans with modern ones and controlling fan speed to match air flow requirements.
- Using grain stirrers in on-floor dryers to obtain more even drying and reduce drying time
- Install moisture sensors to more accurately control the drying process and save fuel by preventing over drying.
- Recovering heat from the cooling section of high temperature dryers to pre-heat drying air.

A1.19.2 Abatement rate

Table 39 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Energy CO_2	Optimised grain drying, storage and ventilation: -4% energy use across the cereals sector	UK	(Warwick HRI and FEC Services 2007)
Energy CO_2	Grain stirrers can reduce length of time taken to dry and reduces spoilage	UK	http://cereals.ahdb.org.uk/media/268962/pr520.pdf
Energy CO_2	Moisture sensors: -40% energy consumption	UK	http://www.louthtractors.co.uk/library/Control_Monitoring.pdf
Energy CO_2	Heat recovery: -15% fuel consumption	UK	http://www.alvanblanchgroup.com/continuous-double-flow-grain-driers
Energy CO_2	Heat recovery: -33% energy consumption	Japan	(Aziz *et al.* 2011)
Energy CO_2	Temperature Differential Controller: -40% energy costs	UK	http://martinlishman.com/automatic-crop-monitoring-and-control/

A1.19.3 Related technologies

Table 40 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Biomass boiler	Biomass boiler, fuel storage and heat exchanger	50/100kW system : £383 kW^{-1} >100kW: £208 kW^{-1}	Fuel for boiler and maintenance costs (*circa* £0.05 kWh^{-1})	(DECC 2013)
Efficient fans and controllers	Upgrading to modern systems resulting in increased efficiency and lower running costs	High	reduced	(Warwick HRI and FEC Services 2007)
Grain stirrers	Harvest Maxi-Stirrer	£15,000 - £20,000	Running cost	Harvest installations retail price list 2014
Moisture sensors	Accurately control drying, prevent over drying	£1,900-20,000 depending on detail	£216 – £540 y^{-1}	http://www.fwi.co.uk/machinery/high-tech-moisture-sensing-at-uk-grain.htm
Heat recovery	Case study of boiler and heat exchanger. Cost using gas/oil: £8 – 14 (t cereal)$^{-1}$, cost using heat recovery: £0.30 (t cereal)$^{-1}$	Information not available		http://www.turnbull-scott.co.uk/pdf/case-studies/woodend-farm-case-study.pdf

A1.19.4 Issues around implementation, current uptake

Installing new grain dryers can help significantly reduce energy use on farm, however, the installations costs can be high with a long payback. Farmers with grain dryers that are near the end of their life will be looking into this new efficient technology, however, some grain dryers can last 20 years. As a result for many farmers the cost implication of changing their system at present would not be a financially viable solution.

Using grain stirrers will decrease drying time but could also increase fuel use in some cases.

A1.19.5 Environmental co- effects

Improving the energy efficiency of drying could reduce spoilage and as a result reduce crop wastage, which in turn would lower emissions.

A1.19.6 Recommendations for further work

Potentially a study may need to take place to see the age and quality of grain dryers throughout Scotland to see if the new technology would have a significant impact on reducing GHG emissions.

A1.20 Energy efficient milking and milk handling

A1.20.1 GHG reduction mechanism

The main GHG production associated with milking and milk handling relates to the energy used in milk cooling, in water heating for equipment cleaning and in creating a vacuum for the milking process.

A1.20.2 Abatement rate

Table 41 Data from literature on abatement by the mitigation option

Abatement	Emission reduction	Country	Reference
Energy CO_2	Heat recovery: 4.9-7.06 t CO_2 y^{-1} (based on 365 litre cylinder requiring 80°C twice a day from ambient temp of 15°C)	UK	(Dunn *et al.* 2010)
Energy CO_2	Variable speed vacuum pump: 1.73-4.04 t CO_2 y^{-1}	UK	(Dunn *et al.* 2010)
Energy CO_2	Milk pre-cooling: up to 0.9 kg CO_2 $(100 \text{ litres})^{-1}$	UK	(Dunn *et al.* 2010)
Energy CO_2	Variable speed milk pump: up to 0.5 kg CO_2 $(100 \text{ litres})^{-1}$	UK	(Dunn *et al.* 2010)

A1.20.3 Related technologies

Table 42 Equipment and infrastructure required for the implementation of the mitigation option

Technology	Short description	Capital cost	Annual costs	Reference
Heat recovery	Heat extracted from the cooled milk is used to pre-heat wash water	>£3,500		(Dunn *et al.* 2010)
Variable speed vacuum pump	On demand vacuum pumps supply vacuum only at the rate required to meet the demand of the system	>£3,200		(Dunn *et al.* 2010)
Plate coolers and controls	Milk is pre-cooled in a plate cooler using cold water. Controls which alter water flow and milk flow to maximise cooling effect in the plate cooler reduce the need for electricity to provide cooling effect in the milk tank	Informati on not available		(Dunn *et al.* 2010)
Variable speed milk pump	Slows the rate of flow of milk through the plate cooler when possible to maximise the cooling effect of the available water supply. Should be considered after existing system has been optimised	£2000		(Dunn *et al.* 2010)

A1.20.4 Issues around implementation, current uptake

Dairy farming is currently having a difficult time and capital for investment is low.

Savings from individual components of a dairy are often interrelated and consideration of milk cooling and water heating needs to be made as a whole. Potential savings from one element may be negated by poor efficiency of another. Savings can often be made by optimising existing equipment at no or little cost. This should be carried out prior to investing in new equipment.

Adoption of renewable heating and associated incentive payments can often negate the potential financial benefits from energy efficiency measures in the dairy. Integration of renewables needs to be carried out such that in efficiencies in energy use are not encouraged.

A1.20.5 Recommendations for further work

An energy audit of each dairy farm would be advisable prior to allocating any funding. Appropriate measures could then be recommended for each specific site.

Annex 2: Quantitative assessment

Calculations were based on the methodology and assumptions used in the most recent UK agricultural marginal abatement cost curve (MACC) calculations (Eory *et al.* 2015), where possible updated with new and/or Scottish information. The calculations were done for the Scottish agriculture in the year 2030, assuming full uptake of the technologies beyond the current uptake, with an interest rate of 3.5%. The interactions between the mitigation options were not included, i.e. the results show what a single mitigation option could contribute to GHG mitigation if it were implemented on every farm where it is feasible regarding the agronomic constraints *and* if it were the only mitigation option applied on farms.

Precision farming technologies

Following the assumptions used in the UK MACC report, a basic system (auto-steering, yield monitor and VRA N application) is considered in the calculations.

Legumes

The mitigation options 'Legumes in rotations' and 'Legume-grass mixtures' were considered based on the UK MACC report (Eory *et al.* 2015). As no updated or further Scotland specific information was available the UK MACC report assumptions were used.

Feed additives in total mixed ration

Three feed additive options were assessed quantitatively: 'Probiotics', 'Nitrate as feed additive' and 'High fat diet'.

In the case of the mitigation options 'Probiotics' and 'High fat diet' in the calculations it is assumed that the administration of these additives do not require feed mixers on farm (in the first case the additive might be sprinkled on top of the concentrates, while in the latter the concentrate supplier would provide the required concentrates with the increased fat content). However, in some cases it might still be more feasible to purchase a feed mixer to support the implementation of these options. In the UK MACC calculations the mitigation option 'Nitrate as feed additive' was assumed to be implemented only on farms which already have feed mixers. However, in this current project the uptake was widened to all farms, adding the costs of feed mixer systems (feed mixer, software, feed storage). The average cost was reduced to represent that 85% of dairy and 20% of beef farms already have the system in place (Eory *et al.* 2015).

The uptake was compared to current baseline rather than an estimated future baseline uptake, consequentially for 'Probiotics' the uptake was increased to 1 for all livestock categories, and for 'High fat diet' the uptake was increased to 1 for beef and sheep and to 0.95 for dairy (based on an estimate that 5% of the dairy herd currently is on high fat diet).

Slurry acidification

Animal waste management system assumptions were updated based on the latest UK Greenhouse Gas Inventory Report (MacCarthy *et al.* 2015). UK-level data were used as corresponding Scottish data were not found.

For the proportion of liquid manures stored in slurry tanks as opposed to lagoons recent Scottish data is available (85% on a total holding basis (Scottish Government 2014)), but as the information is aggregated on a total holding level and not available on a farm type basis, the existing UK farm type data were used.

Cost data were updated (see Table 44) using the average of the two cost information sources (see Section A1.13.3), assuming that in-tank acidification is implemented. These estimates are significantly lower than the cost estimates of the UK report.

Table 43 Cost assumptions used for slurry acidification (in-tank acidification, lifetime of investment: 10 years)

	Capital cost (£ head^{-1})	Annual costs (£ head^{-1} y^{-1})	Annual N savings (£ head^{-1} y^{-1})
Dairy	5.57	6.98	3.29
Beef	3.27	3.84	1.72
Pigs	1.35	1.82	0.89

Anaerobic digestion of livestock waste

The mitigation option 'Anaerobic digestion' was considered based on the UK MACC report (Eory *et al.* 2015). Three alternative solutions were investigated:

- 250 kW capacity digester to be supplied with cattle manure and maize silage
- 500 kW capacity digester to be supplied with pig and poultry manure and maize silage
- 1000 kW capacity digester to be supplied with maize silage

As no updated or further Scotland specific information was available the UK MACC report assumptions were used.

Annex 3: Methodology

Selection of mitigation options

An initial list of 88 GHG mitigation options were drawn up based on recent reviews of GHG mitigation options (Eory *et al.* 2015, Frelih-Larsen *et al.* 2014). The options were evaluated according to the following criteria:

- Technological investment required for the implementation
- High abatement potential
- High feasibility already demonstrated in the UK or abroad and available on the market
- Low cost

Table 3 presents the mitigation options selected for assessment.

Table 44 GHG mitigation options selected for assessment

Mitigation option
Agroforestry
Precision farming technologies
Low emission N spreading technologies
Legumes in rotations
Reduced tillage
Land drainage
Loosening compacted soils
Feed additives in total mixed ration
Precision and multi-phase feeding
Improved livestock health: John's disease prevention
Precision livestock farming
Covering slurry and farmyard manure
Slurry acidification
In-house poultry manure drying
Anaerobic digestion of livestock waste
Capital investment in fuel efficiency
More efficient heating and ventilation
More efficient crop drying
More efficient milking and milk handling

Qualitative assessment

A rapid assessment of qualitative evidence was conducted via a review of information on the relevant aspects of the mitigation options and related technologies from a range of sources, including peer-reviewed scientific literature, Government reports, commercial information available online and via machinery dealers, and expert knowledge of agricultural consultants and researchers.

Quantitative assessment

The quantitative assessment considered the following five options:

- Precision farming technologies
- Legumes in rotations
- Feed additives in total mixed ration
- Slurry acidification
- Anaerobic digestion of livestock waste

The calculations followed the methodology described in the UK MACC report (Eory *et al.* 2015), with specific assumptions detailed in Annex 2. Some of these options were divided into two or more options, thus in total 10 mitigation options were included in the quantitative assessment.