Non-CO_2 abatement in the UK agricultural sector by 2050

Summary report submitted for the project contract "provision of analysis to quantify non-CO_2 abatement in the UK agriculture sector by 2050, with an emphasis on the potential for innovative or novel measures"

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Abbreviations

3NOP	3-nitrooxypropanol
CCC	Committee on Climate Change
CH_4	Methane
CO_2e	Carbon dioxide equivalent
DA	Devolved Administration
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
MACC	Marginal abatement cost curve
MP	Microbial protein
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia

1 Background

In the 2008 Climate Change Act, the UK has committed to an 80% reduction in its GHG emissions by 2050 (compared to the 1990 baseline). Beyond that statutory commitment, the IPCC (IPCC 2018) indicated that to avoid temperature rises of more than 1.5°C, CO_2 emissions need to reach net zero by around 2050 at the latest and emissions of other GHGs (including CH_4 and N_2O) need to get to the same level by around 2075 globally. Accordingly, the UK and devolved Governments requested the CCC to provide long-term pathways on the UK's transition to a net zero GHG emissions from all sectors of the economy.

The land use sector, including agriculture, provides crucial ecosystem services: it supports the production of food, fibre and fuel, and provides cultural and regulating services, like supplying clean water and air (UK National Ecosystem Assessment 2014). Its role in climate change mitigation is two-fold: it can contribute to CO_2 removal via above- and below-ground carbon sequestration and it can reduce non-CO_2 emissions arising from agricultural production. Agricultural activities contributed 45.6 $MtCO_2e$ (9% of total UK GHG emissions[1]) to the UK's GHG emissions in 2017, while forests and grasslands sequestered 27 $MtCO_2e$, and other land use activities released 17 $MtCO_2e$ emissions (Brown *et al.* 2018).

Recent evidence suggests that releasing a proportion of agricultural land to other uses could save 20-40 Mt CO_2e by 2050 annually (Committee on Climate Change 2018). Low-carbon farming practices can offer a further 9 Mt CO_2e annual reduction in GHG emissions, achievable from 2030 (Committee on Climate Change 2015). Furthermore, on-farm practices which have not been included in previous UK wide analysis could provide additional mitigation (see e.g. MacLeod *et al.* 2015).

Recently the UK national GHG inventory methodology for agricultural emissions has been refined; the new 'smart' inventory estimates the majority of emissions using UK specific emission factors, some of which are dynamically calculated in response to local physical environment and agricultural management. As a result of this refinement, emission estimates from both crop and livestock activities have changed, for example estimates of enteric methane emissions from cattle for the year 2015 are 10% lower in the 'smart' inventory than in the previous submission (Brown *et al.* 2018).

This report briefly summarises the work which was aiming to re-calculate the agricultural GHG abatement potential estimated in the 2015 MACC (Eory *et al.* 2015) considering changes in the inventory methodology under two contrasting future land use scenarios, and to identify further opportunities for GHG mitigation in food production.

[1] Including the emissions from international aviation and shipping

Further work on identifying additional abatement in agriculture is currently being undertaken for Defra's 'Delivery of Clean Growth through Sustainable Intensification' project. On completion of that work, a full report, including the results from this report will be published.

2 Methodology

To quantify the on-farm agricultural abatement potential the marginal abatement cost curve methodology was used (Eory *et al.* 2015), and literature reviews were conducted to summarise the direct effects of GHG abatement options and other effects of alternative food production technologies. This section describes the methodology briefly and provides short summaries of the mitigation options where new evidence has been collected (not for ruminant feed, additive nitrate and slurry acidification, as the scope of this project only allowed their implementation in the MACC but not the collection of new, additional evidence).

2.1 Identifying mitigation measures

A list of potential mitigation measures were drawn up supplementing the long lists of mitigation measures collected in previous studies in the UK and Europe (Eory *et al.* 2015, Frelih-Larsen *et al.* 2014, MacLeod *et al.* 2010, Moran *et al.* 2008) with a rapid assessment of the scientific literature on mitigation measures since 2015. The full list consisted of over 300 measures, which were screened against three criteria: 1) confidence in significant technical abatement, 2) technical feasibility, and 3) risk of negative environmental impact. A list of 48 measures was compiled for the assessment, out of these 29 were excluded from this study as they were being analysed in the Delivery of Clean Growth through Sustainable Intensification project. From the remaining 19 measures, in discussion with CCC, eleven were selected for analysis. Four additional measures which were analysed in the Delivery of Clean Growth through Sustainable Intensification and had abatement and cost assumptions already available were also included in MACC reported here (Table 1). The report from the Delivery of Clean Growth through Sustainable Intensification project will include a further 31 measures.

Table 1 Measures selected for analysis in this report.

ID in MACC	Mitigation measure	Notes
MM12	Nitrification inhibitors	Measure assessed under the Delivery of Clean Growth through Sustainable Intensification project, results included here
MM15	Analyse manure prior to application	
MM18	Take stock off from wet ground	
MM19	Sustainable increase stocking density: cut and carry	
MM21	Higher sugar content grasses	
MM29	Increased uptake of cattle genetic improvement practices using the current breeding goal	Measure assessed under the Delivery of Clean Growth through Sustainable Intensification project, results included here

ID in MACC	Mitigation measure	Notes
MM26	Increased uptake of cattle genetic improvement practices using the current breeding goal, using genomic tools	Measure assessed under the Delivery of Clean Growth through Sustainable Intensification project, results included here
MM27	Shift to lower emissions intensity breeding goal in cattle breeding, using genomic tools	
MM28	Genetic modification of cattle to reduce enteric methane emissions	
MM35	Ruminant feed additive 3NOP	Measure assessed under the Delivery of Clean Growth through Sustainable Intensification project, results included here
MM45	Ruminant feed additive nitrate	Based on 2015 MACC assumptions (new scientific evidence not collected)
MM46	Slurry acidification	Based on 2015 MACC assumptions (new scientific evidence not collected)
-	Industrial production of microbial proteins	Assessment outwith of MACC (as not on-farm measure)
-	Lab meat	Assessment outwith of MACC (as not on-farm measure)
-	Insect production	Assessment outwith of MACC (as not on-farm measure)

2.2 MACC methodology

The methodology followed the MACC method described in Eory *et al.* (2015), with refinements to allow a closer match with the smart inventory emission factors and sector activity data, and to accommodate agricultural land use and productivity projections sourced from the report by Thomson *et al.* (2018). The changes are summarised in Table 2; a full description of the method and assumptions will be included in the report from the Delivery of Clean Growth through Sustainable Intensification project.

Table 2 Summary of changes in the MACC methodology

Activity data for 2050	Two scenarios from (Thomson *et al.* 2018): Business as Usual (BAU) and Multifunctional Land Use (MFLU), data on aggregate categories of land use and livestock numbers and yields
Activity data for 2016	Data from the smart inventory: - Land areas for detailed crop categories and animal numbers for detailed livestock categories for the four DA - Crops: fertilised area, fertilisation rates (6 fertiliser categories), yield, crop N residue - Livestock: live weight, milk yield, grazing ratio, manure management system proportions

Emission parameters	Data derived from the smart inventory: - Soil N_2O emission factors and NH_3 volatilisation fraction for each crop, fertiliser category, DA - CH_4 conversion factor for each livestock category and DA, parameters for direct and indirect N_2O emissions from manure storage
Output metrics	GHG emissions by gases, crop and livestock production changes

2.3 Mitigation measures in the MACC

2.3.1 Nitrification inhibitors (MM12)

Nitrification inhibitors depress the activity of nitrifying bacteria, improving the nitrogen fertiliser's plant availability and reducing N_2O emissions and also nitrate leaching in high rainfall circumstances (Akiyama *et al.* 2010), though in some cases they can increase ammonia (and hence indirect N_2O) emissions (Lam *et al.* 2017). Various compounds have been identified as nitrification inhibitors, probably the most widely studied ones are dicyandiamide (DCD), 3,4-dimethyl pyrazole phosphate (DMPP) and nitrapyrin. Furthermore, urea based fertilisers have a high rate of ammonia volatilisation when applied to soils, due to the urease enzyme released by soil bacteria. This leads not only to ammonia (and indirect N_2O) emissions, but reduces the N plants can utilise. Urease inhibitors delay urea hydrolysis to ammonia, reducing ammonia emissions (Harty *et al.* 2016). Using urea in combination with urease inhibitors and nitrification inhibitors can therefore further reduce N_2O emissions.

Nitrification and urease inhibitors can be injected into the soil together with liquid fertilisers, can be applied as a coating on granular fertilisers and can be mixed into slurry before application. Additionally, they can be spread after grazing to reduce emissions from urine.

In our analysis, we considered the application of nitrification inhibitors with ammonium nitrate fertiliser and nitrification and urease inhibitors with urea applications, and expressed the effect as a change in the soil N_2O emission factor. The current uptake is assumed to be 0%.

2.3.2 Analyse manure prior to application (MM15)

In terms of reducing GHGs, the purpose of analysing the manure prior to application is to ensure that the N applied to the crop as organic and inorganic N matches the requirement of the crop. An accurate assessment of the N available from the manure means that the potential for losses of N from the system is minimised. This requires that samples are taken and sent for analysis shortly before application as the period of storage of the manure can affect the N content.

The mitigation is expressed as a reduction in the synthetic N used, as more organic N is utilised. The current uptake is assumed to be 23%.

2.3.3 Take stock off from wet ground (MM18)

In many parts of the UK, livestock are routinely allowed to graze pastures throughout the winter period, providing advantages like reduced housing and feed costs. However, the livestock, particularly in wet periods, can cause soil compaction, increasing water pollution and promoting hotspots of N_2O emissions. Moving stock from wet ground during periods when soil water content exceeds a threshold value can help prevent soil compaction. Animals can be relocated to specially designated stand-off pads (Buss *et al.* 2011). A New Zealand study demonstrated a reduction of up to 12% of total GHG emissions could be achieved by removing cattle from wet ground (Van der Weerden *et al.* 2017). It was also shown that the maximum emissions savings would be achieved with this management approach was applied to poorly drained soils.

The construction of such standoff pads represents a considerable capital investment, but it has been estimated to cost one tenth of the capital costs of a conventional built housing. The abatement is estimated via changing the proportion of manure in the different manure management systems and via decreasing the emission factor, which describes the proportion of N converted to N_2O from urine and dung deposited during grazing. The current uptake is assumed to be 1.5%.

2.3.4 Sustainable increase stocking density: cut and carry (MM19)

Alternatives to the use of grazed pastures for high yielding dairy cows have been explored recently as a means of increasing productivity and stocking density. It has been argued that maintaining cattle indoors can allow better control of feedstocks, and avoid the damage caused to pastures by soil compaction and forage disturbance (Cameron *et al.* 2018) and would allow for reduced emissions from livestock excreta.

In a large experimental study two alternative management systems were compared at the dairy research Centre in Scotland (Hargreaves *et al.* 2016). The study involved a comparison between a traditional pasture fed dairy herd (control) with a cut and carry system in which housed animals were fed during the day with freshly cut grass and provided with total mixed rations overnight. A second system involved housed animals receiving a continuous supply of total mixed rations.

The measure is only assumed to be applied in farms where animals are already partially housed throughout the summer months. The GHG effects of the measure is estimated via a change in the percentage of time spent grazing, leaving the ration composition constant, and a 5% increase in milk yield based on the assumption of improved grass yield utilisation. This implies an increase in the proportion of manure stored and a decrease in the proportion of manure deposited via grazing. The animals' energy need for activity is also reduced due to the lower activity. The current uptake is assumed to be 0%.

The measure showed increased emissions in excess of increased yield: total dairy emission increased by 0.2%, while milk yield increased by 0.18%. The emission increase was mainly due to the increased CH_4 and N_2O emissions from manure. Given the increase in emissions and emission intensity, the measure was excluded from the MACC.

2.3.5 Higher sugar content grasses (MM21)

The incorporation of high sugar grasses into swards is a management option for pasture-based systems. These are ryegrass varieties that have been bred to express elevated concentrations of water-soluble carbohydrate. When digested by ruminants, they have the potential to increase the efficiency of the use of N released from the digested forage (Parsons *et al.* 2011). Consequently, HSGs have the potential to reduce the proportion of ingested N lost in the form of urine, which results in a reduction in N lost through leaching and N_2O emissions (Foskolos and Moorby, 2017; Parsons *et al.* 2004). However, the water soluble carbohydrate (WSC): crude protein (CP) ratio of the grass is critical in controlling the N excreted (Parsons *et al.* 2011).

To estimate the changes in GHG emissions associated with this measure, the milk yield of the cows was increased by 6.8% (total production was kept constant, i.e. livestock numbers have decreased in this option), and the digestible energy content of the roughage was also increased (overall 9% decrease in the N excretion relative to energy corrected milk). The current uptake is assumed to be 9%.

2.3.6 Cattle breeding measures

Many production and fitness traits have been shown to have a genetic component and have scope to be improved via genetic selection. Current broader breeding goals that select on both production and fitness traits can help to mitigate GHGs from livestock systems per unit of output, due to a combination of lower feed intake, higher yield and fewer non-productive animals in the herd. GHG emissions can be reduced if the output is kept constant. The reduction in dairy cattle numbers in the past two decades in the UK was accompanied by an increase in milk production and a decrease in enteric CH_4 emissions from dairy cattle (Brown *et al.* 2016, Brown *et al.* 2018). Similarly, increased growth rate enables beef animals to reach slaughter age quicker, reducing their lifetime emissions. Garnsworthy (2004) estimated, using modelling, that if cow fertility was restored to 1995 levels (from the 2003 level) that methane emissions from the dairy industry could be reduced by 10-15%.

So far, improvement in cattle production and efficiency using the current breeding goals has been happening. However, use of better genetic material has only reached an uptake of around 20-25% in the dairy herd, and still lower in the beef herd (Defra 2018). An increased uptake will lead to further improvements in

efficiency. Though it is expected that the efficiency is going to continue to increase without further policy intervention, a more widespread and therefore larger increase in milk yield and growth rate can be expected from increased adoption of the best available genetic material. Measure 29 (Increased uptake of cattle genetic improvement practices using the current breeding goal) is representing this mitigation measure.

Genetic improvement in the national herd can be enhanced by using genomic tools (measure 26: Increased uptake of cattle genetic improvement practices using the current breeding goal, using genomic tools). This entails farmers collecting performance information on the individual animals and genetic testing, and feeding back these information to breeding goal development.

Literature suggests that the genetics of mammals have an influence on the micro-organisms present in the gut (Hegarty and McEwan, 2010). It is possible to select sheep for high or low CH_4 emissions, as CH_4 production is heritable to some extent (Pinares-Patiño *et al.* 2013); selection for low emission causes changes in the animal's nutritional physiology (Goopy *et al.* 2014). Studies indicate potential genetic selection for low CH_4 emission for dairy cattle too (de Haas *et al.* 2011, Roehe *et al.* 2016). Inclusion of low enteric CH_4 emission in the breeding goal (measure 27: Shift to lower emissions intensity breeding goal in cattle breeding, using genomic tools) could reduce CH_4 emissions from cattle, though might limit the productivity and fitness improvements to some extent.

Measure 28: Genetic modification of cattle to reduce enteric methane emissions is a mitigation measure which is speculative at the moment, assuming that genetic modification could be found which reduces enteric CH_4 emissions.

The breeding measures as modelled in the MACC cannot be applied to the same animals as MM26 assumes MM29 is implemented (and includes those effects), and both MM27 and MM28 includes both MM29 and MM26. However, they could still be applied in parallel within the national herd – this is reflected in the interactions in the MACC.

2.3.7 Ruminant feed additive: 3NOP (MM35)

3NOP (3-nitrooxypropanol) is a chemical that reduces the production of enteric methane by ruminants when added to their rations. It does so by reducing the rates at which rumen archaea convert the hydrogen in ingested feed into methane. Specifically, 3NOP inhibits methyl-coenzyme M reductase, the final step of CH_4 synthesis by archaea (Duin *et al.* 2016). In a meta-analysis, Dijkstra *et al.* found that the effect on enteric CH_4 emissions was -38.8%+/-5.5% for dairy and -17.1%+/-4.2% for beef cattle (2018).

The measure entails the ingestion of a small amount of 3NOP each day, typically in the range of 0.05-0.2 g NOP for each kg of dry matter intake (Jayanegara *et al.*

2018). For housed animals the 3NOP could be mixed in with the ration. The current uptake is assumed to be 0%.

2.3.8 Summary of assumptions used in the calculations

Table 3 shows the assumptions for each measure in the MACC calculations.

Table 3 Assumptions for the measures

	Emission parameter / input changes	Current uptake	Applicability	Costs (besides changes in crop / milk / meat yield and N use)
Nitrification inhibitors	EF1 for AN -25%, EF1 for urea -50%	0	all crops only AN and U fertilisers = 1.00	fertiliser cost difference: +£0.5/kg N for ammonium nitrate and +£0.587/kg N for urea
Analyse manure prior to application	-5.5kg of total fertiliser per hectare fertilised	0.23	all crops and grasslands = 0.30, but 0 for winter crops	manure analysis £30/holding/y (assuming average 60 ha)
Take stock off from wet ground	time spent grazing: -8.3%; daily spread FYM: increase as much as grazing got reduced; N2O direct emission factor from grazing: -5%	all beef cattle = 0.015	all beef cattle = 0.24	construction cost: £654/animal, lifetime 15 year; maintenance: £32/animal/y
Sustainable increase stocking density: cut and carry	time spent grazing: 0; milk yield: +5%	0	dairy cows = 0.50	trailer/mixer wagon: £35,000 for 80 cows, lifetime 5 years
Higher sugar content grasses	roughage digestible energy content: increased to 75%; milk yield: +6.8%	all dairy cattle = 0.09	all dairy cattle = 0.29	HSG seed price difference: £67/ha for 5 years, on average 1.8 livestock unit/ha stocking density
Increased uptake of cattle genetic improvement practices using the current breeding goal	dairy: milk yield: +0.9%/year; milk protein: +0.9%(of % value)/year; cow fertility: +0.38%(of % value)/year /// beef: live-weight: +0.25 %/year; growth rate: +0.25 %(of % value)/year; cow fertility: +0.25 %(of % value)/year	0	dairy cows =0.9, all beef cattle = 0.2	dairy: £0.5 million research investment in the UK, lifetime 20 years; genomic tools recurring cost: £0.25 million every 5 years; genomic testing cost: £20/bull, serving 500 cows /// beef: £1.5 million research investment in the UK, lifetime 20 years; genomic tools recurring cost: £0.25 million every 5 years; genomic testing cost: £20/bull, serving 100 cows

	Emission parameter / input changes	Current uptake	Applicability	Costs (besides changes in crop / milk / meat yield and N use)
Increased uptake of cattle genetic improvement practices using the current breeding goal, using genomic tools	dairy: milk yield: +0.75%/year; milk protein: +0.75%(of % value)/year; cow fertility: +0.3%(of % value)/year; enteric CH4 conversion factor: -0.15%(of % value)/year /// beef: live-weight: +0.25 %/year; growth rate: +0.25 %(of % value)/year; cow fertility: +0.25 %(of % value)/year; enteric CH4 conversion factor: -0.15%(of % value)/year	0	dairy cows =0.45, all beef cattle = 0.2	dairy: £2.5 million research investment in the UK, lifetime 20 years; genomic tools recurring cost: £0.5 million every 5 years; genomic testing cost: £20/bull, serving 500 cows /// beef: £2.5 million research investment in the UK, lifetime 20 years; genomic tools recurring cost: £0.5 million every 5 years; genomic testing cost: £20/bull, serving 100 cows
Shift to lower emissions intensity breeding goal in cattle breeding, using genomic tools	dairy: milk yield: +0.75%/year; milk protein: +0.75%(of % value)/year; cow fertility: +0.3%(of % value)/year; enteric CH4 conversion factor: -0.4%(of % value)/year /// beef: live-weight: +0.25 %/year; growth rate: +0.25 %(of % value)/year; cow fertility: +0.25 %(of % value)/year; enteric CH4 conversion factor: -0.4%(of % value)/year	0	dairy cows =0.45, all beef cattle = 0.1	dairy: £5 million research investment in the UK, lifetime 20 years; genomic tools recurring cost: £0.5 million every 5 years; genomic testing cost: £20/bull, serving 1000 cows /// beef: £10 million research investment in the UK, lifetime 20 years; genomic tools recurring cost: £0.5 million every 5 years; genomic testing cost: £20/bull, serving 1000 cows
Genetic modification of cattle to reduce enteric methane emissions	milk yield: +0.6%/year; milk protein: +0.6%(of % value)/year; cow fertility: +0.25%(of % value)/year	0 (as the modelled improvements are additional to the changes due to current uptake)	dairy cows =0.9, all beef cattle = 0	0
Ruminant feed additive 3NOP	dairy: enteric CH4 conversion factor: -30%(of % value) /// beef: enteric CH4 conversion factor: -20%(of % value)	0	equals to the time housed for all cattle	£38/animal/y

	Emission parameter / input changes	Current uptake	Applicability	Costs (besides changes in crop / milk / meat yield and N use)
Ruminant feed additive nitrate	enteric CH4 conversion factor: -17.5%(of % value)	0	applicability values in 2015 MACC: 0.85 for all dairy but calves, 0.2 for all beef but calves, calves 0 - these values are modified with: i) grazing (i.e. 2015 MACC applicability multiplied by non-grazing %) and ii) calve ratios (i.e. 2015 MACC applicability multiplied by 0.5 to account for calves in animal categories where applicable)	dairy: £27.00/animal/y /// beef: £14.50/animal/y
Slurry acidification	slurry tank CH4 conversion factor: -75%(of % value); slurry tank N volatilisation factor: -70%(of % value)	0	dairy, beef, pigs: all slurry tanks	dairy: £45.82/animal/y /// beef: £35.59/animal/y /// pigs: £6.88/animal/y

3 Results

3.1 Marginal abatement cost curves

The measures were modelled for the year 2050 for the UK, England and the Devolved Administrations, using two agricultural land use and productivity projections (Thomson *et al.* 2018) and with five different uptake level assumptions. The tables below show a selection of these scenarios. The full set of results will be published in the report on the project 'Delivery of Clean Growth through Sustainable Intensification', commissioned by Department for Environment, Food and Rural Affairs.

Table 4 MACC, 2050, UK, maximum technical potential, BAU agricultural activity

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})	CH_4 abatement (kt CO_2e y^{-1})	N_2O abatement (kt CO_2e y^{-1})	Milk production change (t year^{-1})	Meat production change (t year^{-1})
HighSugarGrasses	MM21	-1,790	26	16	10	227,237	0
BreedingCurrent	MM29	-747	565	317	248	0	-28,383
BreedingGenomics	MM26	-735	823	500	323	0	-72,114
BreedingLowCH4	MM27	-2,495	110	75	35	0	-49,705
GMCattle	MM28	-9,151	11	8	3	0	-33,388
ManureAnaysis	MM15	-615	4	0	4	0	0
SlurryAcid	MM46	61	926	958	-32	0	0
NitrateAdd	MM45	64	725	725	0	0	0
3NOP	MM35	108	2,055	2,055	0	0	0
NitrifInhibitor	MM12	1,565	151	0	151	0	0
StockOffWet	MM18	4,994	26	14	11	0	0

Table 5 MACC, 2050, UK, 75% uptake, BAU agricultural activity

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})	CH_4 abatement (kt CO_2e y^{-1})	N_2O abatement (kt CO_2e y^{-1})	Milk production change (t year^{-1})	Meat production change (t year^{-1})
HighSugarGrasses	MM21	-1,790	16	10	6	144,863	0
BreedingCurrent	MM29	-747	424	238	186	0	-21,287
BreedingGenomics	MM26	-730	622	378	244	0	-54,085
BreedingLowCH4	MM27	-2,365	87	59	28	0	-37,279
GMCattle	MM28	-8,298	9	7	3	0	-25,041
SlurryAcid	MM46	61	695	718	-24	0	0
NitrateAdd	MM45	64	546	546	0	0	0
3NOP	MM35	106	1,561	1,561	0	0	0
NitrifInhibitor	MM12	1,563	114	0	114	0	0
StockOffWet	MM18	4,994	19	10	8	0	0

Table 6 MACC, 2050, UK, maximum technical potential, MFLU agricultural activity

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})	CH_4 abatement (kt CO_2e y^{-1})	N_2O abatement (kt CO_2e y^{-1})	Milk production change (t year^{-1})	Meat production change (t year^{-1})
HighSugarGrasses	MM21	-1,790	19	12	7	171,831	0
BreedingCurrent	MM29	-747	427	240	187	0	-21,463
BreedingGenomics	MM26	-708	647	395	253	0	-55,710
BreedingLowCH4	MM27	-2,323	90	61	29	0	-38,765
GMCattle	MM28	-8,754	9	6	2	0	-25,836
ManureAnaysis	MM15	-601	3	0	3	0	0
SlurryAcid	MM46	61	720	744	-24	0	0
NitrateAdd	MM45	64	550	550	0	0	0
3NOP	MM35	108	1,606	1,606	0	0	0
NitrifInhibitor	MM12	1,565	151	0	151	0	0
StockOffWet	MM18	4,994	20	11	9	0	0

3.2 Alternative food production methods

3.2.1 Industrial production of microbial proteins

Single-cell protein is protein extracted from cultivated microbial biomass such as algae, bacteria and fungi, collectively known as microbial protein (MP) (Upadhyaya *et al.* 2016). MP offers a potentially high-quality alternative to protein sources for

livestock (Matassa *et al.* 2016) and also as a direct food source for humans, forming the basis of popular brands such as Quorn, Marmite and Vegemite (Cumberlege *et al.* 2016). In recent years research and development in both scientific and industrial domains has been gaining momentum, spurred on by steep increases in the price of high protein feed (Matassa *et al.* 2016) and the progress made in industrial fermentation technologies (Pikaar *et al.* 2017).

The greatest environmental benefits can be seen when humans consume microbial proteins directly in place of meat or other land intensive crops. Mycoprotein (single celled protein derived from fungi), are particularly suited to mimic the taste and consistency of meat (Mattasa *et al.*, 2016). Mycoprotein production however involves high production costs, which at present mean it is comparably priced to meat. Research exploring the potential of algae and bacteria as a source of direct protein for humans is ongoing, however, issues with high nucleic acid content and low digestibility continue to limit their use as a food source (Nasseri *et al.*, 2011).

Single-cell protein offers a potential alternative to traditional high protein animal feed such as fishmeal and soymeal. Studies have shown high MP feed substitution potential for all major livestock categories (cattle, pigs, poultry, fish) without negative consequences on animal productivity and wellbeing (Øverland *et al.*, 2001; Hellwing *et al.* 2007; de Lima *et al.* 2012; Schøyen *et al.* 2007).

The environmental impacts of an increased uptake of microbial protein as animal feed has been modelled recently by Pikaar *et al.* (2018). They found that a 7% reduction in agricultural GHG emissions, 8% reduction in N surplus and 6% reduction in cropland areas could be achieved if 6% of conventional crop-based animal feed were replaced by MPs (234 Mt MP dry matter annually), given the feedstock for MP was 'agriculture free' (hydrogen generated by renewable energy). However, such a production route would require around 10% of the combined installed solar and wind energy. Other recent work has compared the cradle to factory gate water use, land use and carbon footprint of FeedKind™, a new MP product recently approved for use in organic feed (Cumberlege *et al.* 2016) (Table 7). The products have higher GHG emissions than soy protein concentrate, but lower water consumption and land occupation.

Table 7 Impacts of feed ingredient in relation to protein content, taking a cradle to factory gate LCA (using information from Cumberledge et al. 2016)

Ingredient	Protein content (% dry matter)	GHG emissions (kg CO_2e (kg protein)$^{-1}$)	Water use (m^3 (kg protein)$^{-1}$)	Land use (m^2 (kg protein)$^{-1}$)
FeedkindTM Pellet	71	2.648	0.029	0.052
FeedKindTM Powder	71	2.229	0.01	0.000*
Fish meal	64	2.640	0.024	0.011
Soy protein concentrate	66	0.791	0.136**	6.655**

*no land occupation as no vegetable oil used to bind power into pellet

**based on soybean water and land consumption

3.2.2 Lab meat

Lab meat, also known as cultured meat, describes meat produced outside a living animal (Alexander *et al.* 2017). It has been proposed as a means of addressing ethical and environmental concerns associated with conventional meat production (Bryant & Barnett, 2018), whilst offering consumers a product that aims to mimic meat in its characteristics and appearance.

The process, sometimes referred to as cellular agriculture, combines biotechnology with various tissue-engineering techniques to produce meat from cell cultures in a laboratory setting (Gaydhane et al. 2015). These cells are cultured in a feedstock that contains the nutrient and energy sources required for division, differentiation and growth of cells into muscle cells that form tissue (Bhat et al. 2015). Different inputs can be used to produce the nutrient 'broth' in which cells are cultured, including cyanobacteria and plant-based alternatives (Tuomisto and Teixeira de Mattos 2011). As only muscle tissue is developed, it is hypothesised that when the technology is fully developed the amount of energy and nutrients needed may be relatively small compared with those needed to grow and sustain a whole animal (Alexander *et al.* 2017). Cultured meat is not yet commercially viable to produce, although prices have been rapidly falling. Large scale production, bringing economies of scale, requires further research, though some suggest the product might be available by 2021 (Verstrate, 2016).

Cradle to factory gate assessment estimated that if cyanobacteria are used as feedstock, the production of cultured meat would involve 7–45% less energy, 78–96% lower GHG emission, 82–96% lower use of water and 99% lower land use than conventional meat production (Tuomisto and Teixeira de Mattos 2011). However, using cyanobacteria as growth medium for tissue production is still under development and currently available plant based alternatives offer substantially smaller improvements. The high direct energy used in production of lab meat suggests that a low-cost and low-carbon source of energy may be a prerequisite for cultured meat to be environmentally viable (Table 8).

Table 8 Environmental impact of producing alternative meat production systems (Mattick et al. 2015, Tuomisto and Teixeira de Mattos 2011, Williams et al. 2006)

	GHG emissions (kg CO_2e (kg protein)$^{-1}$)	Water use (m^3 t^{-1} (kg protein)$^{-1}$)	Land use (m^2 (kg protein)$^{-1}$)	Energy use (MJ (kg protein)$^{-1}$)
Beef	160	57	79	279
Pork	54	16	63	144
Sheep	147	96	42	199
Poultry	34	7.3	47	88
In vitro meat	10.6-36.8	2.22	5.33-26.3	156-553

3.2.3 Insect production

Insect farming – as opposed to wild harvest – for food and feed is a commercial activity, both in tropical and temperate countries. The EFSA Scientific Committee (2015) lists nine species which are known to be farmed for human consumption (including crickets, locusts, mealworms), and further six which are produced as animal feed. The nutritional content of insects are favourable; they are high in fats, protein and micronutrients, though composition varies highly with the species and the development stage (van Broekhoven *et al.* 2015).

Insects are environmentally attractive option as a protein source for two main reasons. They are more efficient in converting biomass into calories and protein than other livestock mainly because they are poikilothermic and thus require less energy for maintenance. Secondly, insects have a higher proportion of edible parts than other livestock, often reaching 100%. This results in a more efficient feed conversion: mealworms are reported to require 2 kg feed per 1 kg gain in liveweight (Oonincx and de Boer 2012), while poultry, pigs and beef need 4 kg, 8 kg and 24 kg food, respectively, for 1 kg gain in liveweight (van Huis *et al.* 2013). While insects compare favourably with other livestock protein sources regarding GHG emissions, their energy use is higher than of other protein sources, and their land use only becomes favourable if waste is used as a feedstock rather than primary crop products (Table 9). Similarly, insects can deliver more environmental benefits if they are used as human food rather than animal feed. Though they are already available and consumed in Europe, public acceptance of insect based meals will need to increase before insects would replace a significant proportion of meat in the diet (Caparros Megido *et al.* 2016, Sogari *et al.* 2018).

The production costs are currently too high to be competitive with mainstream (plant) protein sources; but insect meal is already occupies a niche market in high value sectors (aquaculture) as a replacement for fishmeal. Efficiency can be expected to increase and costs to decrease with increasing volume of production, also likely decreasing the emission intensity and land use and energy impacts. If legislation changes to allow livestock excreta as a substrate, insects could deliver more value to manures and livestock by-products than anaerobic digestion does.

Table 9 Environmental impacts of protein produced from various sources

Protein source	GHG emissions (kg CO_2e (kg protein)$^{-1}$)	Energy use (MJ (kg protein)$^{-1}$)	Land use (m^2 (kg protein)$^{-1}$)	Reference
Mealworm[1]	13.2 (43% from energy use)	167.2	17.7	(Oonincx and de Boer 2012)
Housefly larvae[2]	1.4 (51% from energy use)	17	0.1	(van Zanten *et al.* 2015)
Black soldier fly larvae[3]	2.1	15.1	0.05	(Salomone *et al.* 2017)
Soybean	1.7	4.1	8.7	(Salomone *et al.* 2017)
Beef	75-170	177-273	144-258	(de Vries and de Boer 2010)

Protein source	GHG emissions (kg CO_2e (kg protein)$^{-1}$)	Energy use (MJ (kg protein)$^{-1}$)	Land use (m^2 (kg protein)$^{-1}$)	Reference
Pork	21-53	95-236	47-64	(de Vries and de Boer 2010)
Chicken	18-36	80-152	42-52	(de Vries and de Boer 2010)
Eggs	30-38	87-107	35-48	(de Vries and de Boer 2010)
Milk	24-38	37-144	33-59	(de Vries and de Boer 2010)

[1] Substrate: grain and carrot; waste from mealworm production not considered

[2] Substrate: food waste and poultry manure; indirect impacts included (alternative use of substrate, use of insect waste, use of insect meal (replacing soybean meal))

[3] Substrate: food wastes; indirect impacts included (alternative use of substrate, use of insect waste, use of insect meal (replacing soybean meal))

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