Delivering Clean Growth through Sustainable Intensification

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Project identification

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   Delivering Clean Growth through Sustainable Intensification

3. Contractor organisation(s):
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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Background

The UK Government's proposed approaches to meet greenhouse gas reduction targets by both 2032 and by 2050 are outlined in policy documentation such as the Clean Growth Strategy (UK Government, 2017) and the 25 Year Environment Plan (UK Government, 2018). The Delivering Clean Growth through Sustainable Intensification project (DCGtSI) was commissioned by Defra to better understand the appropriate mitigation methods that could be applied to English farming to meet climate and productivity targets in the future. Even mitigations methods (MM) that have a positive return are not necessarily taken up widely and need an effective set of incentives to encourage their adoption. Farming is a confluence of multiple decision-making strategies and the various goals of individual land use managers, limited biophysical capacity and financial leverage affect progress towards established targets and ambitions.

The objectives work were to:

1) Identify the most promising greenhouse gas (GHG) mitigation approaches with the highest technical potential
2) Refine these approaches through the lens of social acceptance and farm level testing in order to ensure uptake of the most feasible technologies
3) Define feasible trajectories for English farming up to 2050 (with lessons for other UK farming communities) under 3 mitigation scenarios
4) Establish mechanisms for policy intervention to meet 2050 GHG goals for English farming systems (with lessons for other UK farming communities)

These are achieved through four work packages:

Work Package 1: Synthesis and extension of knowledge on mitigation methods appropriate for on-farm adoption. The most appropriate mitigation measures were developed through a series of steps, namely i) augmenting a previous list of 297 MMs developed since 2008 (and updated most recently in 2015 (Eory et al., 2015)) with an additional 32 measures that had become more viable since 2015; ii) a review for applicability of these MMs led to a 'medium' list of 85 measures that could be applied on farm in England; iii) assessment of these MMs against the level of confidence in abatement potential, their technical feasibility and the risk of negative environmental impacts from their adoption with detailed descriptions of their key features. In addition, Defra requested a further number of MMs to be added which led to a final list of 39. Broadly these MMs covered cropland management, grazing land management, management of organic soils, restoration of degraded lands, livestock management, housing and manure, land use change, energy efficiency and a category covering 'others', such as vertical farming. The MMs' potential abatement and cost-effectiveness (financial cost of GHG saving) in England were estimated. Generally, the most promising measures in terms of cost-effectiveness were those around: agro-forestry, the correct use of liming of cropland, biological N fixation in grass, nitrification inhibitors, cattle breeding, ruminant health and 3NOP. The Marginal Abatement Cost Curve (MACC) was reviewed and scrutinised by three independent expert reviewers to ensure the evidence and its implementation is robust.

Work Package 2: Improving the understanding of social factors surrounding these mitigation measures. The final list of MMs from WP1 provided the basis for establishing the barriers to uptake in more depth. A two phase approach was applied. Firstly a stakeholder consultation and workshop were used to identify the appropriate MMs for each farming sector, based on their suitability and applicability within their commodity supply chains. This involved circulating the MMs for scrutiny to 25 industry stakeholders, such as Natural England, Agricultural Industries Forum and the NFU. The results of these interviews were synthesised at a stakeholder workshop. The workshop produced a refined list of MMs for presentation to farmers at 6 sector-specific workshops where farmers ranked them by feasibility and effectiveness. Farmers also ranked incentives for encouraging adoption and considered barriers to uptake. The sectors engaged were: arable crops including vegetables, combinable crops, lowland beef and sheep, less intensive beef and sheep, upland livestock and specialist dairy.

Work Package 3: Develop a set of three scenarios setting out alternative mitigation strategies. The adoption scenarios from WP2 helped to inform a social science driven model of

mitigation trajectories up to 2050. Three scenarios were identified by Defra, namely a scenario which focuses solely on maximising GHG mitigation; a scenario which focuses solely on minimising on-farm cost; and a scenario which focuses on maximising co-benefits. Each mitigation method was assessed against possible drivers - identified in WP2 - to derive a potential uptake level from the present adoption of MMs (*low, medium and high*). These assumptions were tested at a workshop with policy representatives and NGOs. Trajectories were then developed across England and by region (Table 1).

Table 1: Mitigation in 2050 for each scenario and region.

2050 Mitigation Mt CO_2e	England	East of England	South West	Yorkshire & Humber
High Mitigation	13.62	2.76	3.09	1.45
Low Cost	7.25	1.07	1.88	0.78
Co-Benefits	8.37	2.49	1.49	0.86

The high mitigation trajectory would lead to the highest saving of just under 14 Mt CO_2e. Against the latest (2018) estimates for the Agriculture sector GHG emissions (see: https://naei.beis.gov.uk/reports/reports?report_id=1000) this constitutes a reduction – at the high mitigation scenario - of 50%. For the low cost scenario this is 27% of current emissions from agriculture, and 31% for the co-benefits scenario. Though note that some of the MMs cover land use change and waste management so not all of the emissions reduction would be reported in the Agriculture sector of the inventory. The results provide some inference on the wide variability of strategies for intervention as well as regional indications of which set of measures would be most effective. This argues for a regional approach to implementation which may mean that mitigation would require both integrated landscape and farm level approaches.

Work package 4: Establish mechanisms for policy intervention to meet 2050 GHG goals for English farming systems.

The scenario results offer parameters for intervention towards achieving net zero carbon by 2050. The scale of reductions is dependent on the long-term goals of policy. The suite of current policies and interventions for the uptake of sustainable agricultural methods were reviewed. Building on the findings from the literature, an online survey was designed to elicit Defra policy makers' knowledge and experience regarding the suitability of the interventions for supporting mitigation methods. Whilst we recognise the growth in private sector-led incentives, e.g. carbon accounting and labelling, this was not within the scope of the exercise. The survey examined specific MMs but there was an overall agreement for an approach that mixes regulation and voluntary interventions.

In particular the use of fiscal incentives initially but then raising the regulatory baseline to set sustainable practices as standard practice. Clear – and early – sight of these regulatory goals and timeframes would potentially lead to increased uptake of these fiscal incentives as a tool to engage decision-making and structural change. As a backdrop the switch over the next decade from basic payments to Environmental Land Management schemes and other initiatives will change the rationale for agricultural support. This may encourage increased adoption and awareness towards these mitigation measures. Hence, the transition needs to be managed by clear messaging with long-term consistency to encourage acceptance of a future farming industry promoting sustainable methods that are of direct benefit to UK society. It should be noted the results are based on internal commentary from Defra policy, not necessarily reflecting external stakeholder views. The results help give an indication of what interventions may be needed to delivery varying levels of uptake to achieve the mitigation scenarios presented, but do not fully reflect those which are being developed by Defra, this work is ongoing.

Peer review

The work package 1 MACC was reviewed and scrutinised by three independent expert reviewers to ensure the evidence and its implementation is robust. Reviewers presented their comments to Defra and the project team for consideration, this did not highlight any major issues, only suggestions to ensure clear messaging around some of the measures and their underlying assumptions. It was suggested that, in future work, a more systems level (rather than

measures oriented) approach could be taken when looking at net zero since many measures can only really be fully understood in the context of wider production systems.

Further work

The project gained and has continued to gain significant interest from policy makers at Defra, the CCC and BEIS as well as other administrations, e.g. the Scottish Government, and industry, e.g. AHDB. Throughout the project extensions have been made to the contract to extend the number of MMs reviewed in depth to meet policy interest and to explore the consequences of MMs on air quality and develop a further scenario to explore uptake and interactions of certain measure groupings, namely agroforestry and livestock, when payment is used as an incentive. The project has been referenced in a number of documents relevant to climate change in the UK.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the objectives as set out in the contract;
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   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Exchange).

In order to meet internationally agreed targets, the UK has committed to net zero carbon from its industries and services by 2050. Agriculture and land use is a prominent contributor and potential sink for carbon emissions and this has been recognised within a number of documents over the last few years. The technical potential and costs of mitigation technologies can be summarised in marginal abatement cost curves (MACCS). However, whilst economically attractive, farming is a confluence of multiple decision-making strategies and the various goals of individual land use managers may limit progress towards established targets and ambitions.

The scope of this work was to identify the most promising technology bundles for adoption on farm and then assess their feasibility and acceptance within the farming industry and their suitability for application within England's diverse farm context. The objectives of this work were to:

1) Identify the most promising GHG mitigation approaches with the highest technical potential
2) Refine these approaches through the lens of social acceptance and farm level testing in order to ensure uptake of the most feasible technologies
3) Define feasible trajectories for English farming up to 2050 (with lessons for other UK farming communities) under 3 mitigation scenarios
4) Establish mechanisms for policy intervention to meet 2050 GHG goals for English farming systems (with lessons for other UK farming communities)

These objectives were achieved through four work packages aimed to consecutively provide evidence to meet these objectives.

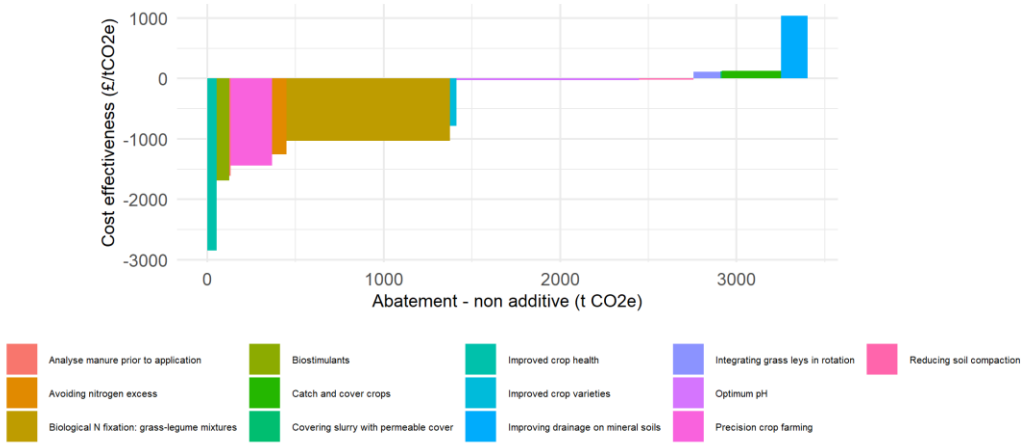
Objective 1. Identify the most promising GHG mitigation approaches with the highest technical potential.

A total of 36 mitigation measures (MMs) were explored in detail and provided as individual fiches to Defra. An original list curated by SRUC from over ten years working on MACC's were screened for their applicability. Specifically, the MMs were developed when considering each MM in terms of i) confidence in abatement potential, ii) technical feasibility and iii) risk of negative environmental impact. The final list covered: cropland management, grazing land and pasture improvement, housing and manure and livestock management as well as 'others' such as vertical farming, switching to static machinery etc. The technical potential and economic costs per unit of GHG mitigation of the options were estimated, together with a qualitative assessment of the wider impacts on the environment and society. For some of these MMs a detailed quantitative analysis could not be undertaken due to the lack of available evidence. Hence more descriptive narratives were provided for these MM's which were added to the list by Defra.

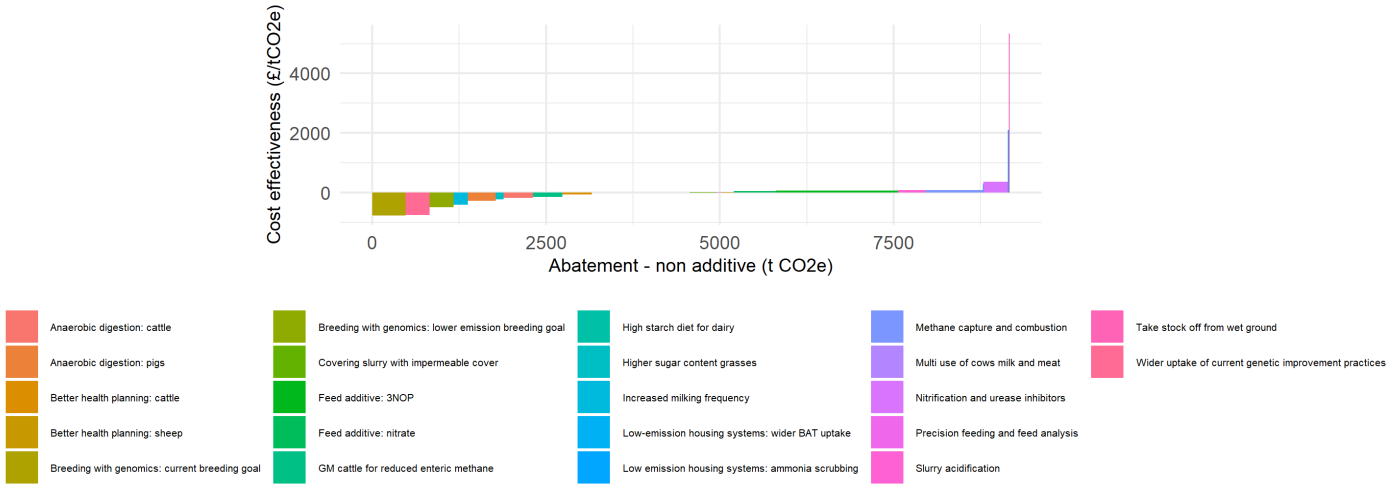
After the final list was agreed with Defra, the likely abatement potential and cost effectiveness (in £/tCO_2e) of these candidate measures were estimated. This is estimated from the change in emissions once the MMs is applied, the change in profit observed, as well as applicability and current uptake of the MMs. To draw MACCs the regional baseline practices are characterised, hence the MACC accommodates changes in current practice. It is important to note that these fiches are 'snapshots' of current knowledge and consequently, in the case where there is limited evidence or as the technology changes, these estimates would be expected to change. Each fiche states the amount of uncertainty around the estimates and, in some cases, monte carlo estimation was used to assess the range of effect. Figure 1 shows the MACCs at the English level for crop, livestock and other measures.

Figure 1. MACCs for English Farming by Sectoral mitigation measures

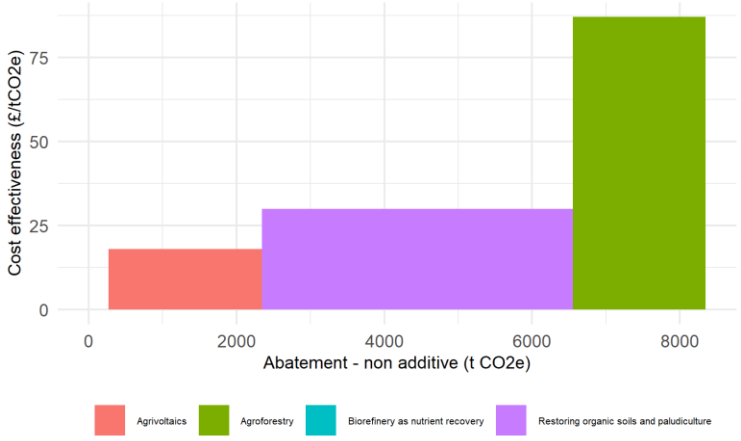
England, 2050, MTP, crop measures



England, 2050, MTP, livestock measures



England, 2050, MTP, other measures



In summary, the MACC's (for cropping, livestock and other measures) show a number of estimates which are below the cost line, i.e. - a win-win effect, and a small number with high costs of intervention. For measures in

the MACC, the results (i.e. the abatement potential and cost effectiveness) includes the effects of interactions between measures, based on estimated interaction factors (IFs). Interactions between measures included in the MACC are considered to be limited. The exception is MM 38.MultUseCows, which is likely to be incompatible with the breeding measures and increased milking frequency. Further detail is provided in the accompanying fiches and Marginal Abatement Cost Curve with Interactions Table. Please note that 'other' measures considered in the MACC represent non ag sector mitigation facilitated by on farm actions.

Objective 2: Refine these approaches through the lens of social acceptance and farm level testing in order to ensure uptake of the most feasible technologies

To further refine the MMs that were considered cost-effective, they were assessed for their suitability for application at farm level. A literature review was initially undertaken to set a conceptual framework and identify the main factors that enable or constrain uptake. Factors were classified into several areas but a more detailed review is available in the project report: 'Deliverable Barriers to uptake of Clean Growth Mitigation methods'. The main areas which emerged from the literature were around farmer related factors, including education and knowledge accumulation, economic factors, farm characteristics and institutional conditions.

This framework was applied to the next stage of consultation with industry stakeholders to refine the MM list. This led to widening the definitions of MMs to ensure understanding within the farming population, for example rather than 'use of catch/cover crops', these were split to include targeted planning for intercropping and use of cover crops. A full list of the recast MMs is provided in Annex A to the report '*Mapping farmer expectations of mitigation measures against economic feasibility'.*

Consultations with stakeholders including AHDB, NFUs and Agricultural Industries Confederation also allowed further elicitation of the barriers to adoption. This discussion offered a rich dialogue raising pertinent issues around why farmers and farming may not be conducive to adoption of these MMs. These are itemised as the main issues around the framework developed from the literature review.

***Farmer Related Factors*:** Statements tended to coalesce around the role of habits and a particular mindset that stakeholders had encountered which is unwilling to change. Effectively this indicates a conservative approach to changing farming systems. General themes discussed were around scepticism towards the newer technologies such as nitrification inhibitors and diet additives, resulting in a lack of confidence in the measures themselves to deliver within a practical farming system. Moreover, a cultural resistance was identified which echoes the idea of a farmer's self-identity towards how a 'good' farmer is perceived by their peers.

Education and Knowledge Accumulation: The main themes that emerged around education and knowledge was the ability to monitor change within the business, record keeping for instance was not considered a natural part of the farming culture. Moreover, a general lack of knowledge about changing methods and the use of new technologies, e.g. variable rate spreaders, which are not being used optimally due to lack of training and knowledge. Moreover, some stakeholders believed there was an unwillingness to embrace new evidence and that negative perceptions of more nature-based approaches due to historic or partial evidence, had created prejudice against change towards these. A final theme in this group focused on lack of good evidence, capacity or support for changing the farming system. The focus of advisors and consultants has mostly been on production efficiencies as opposed to wider social and environmental changes within the farm. Whilst a small number of demonstration farms are integrating more ecological approaches within their systems to show the practical application of these measures and encourage change, the lack of support for such changes in the wider farming community emerged as a commonly identified barrier.

Economic Factors: The major themes that emerged were around the current asset base and the investment required, along with the skills to calculate a payback time for investment for some of the MMs. This echoes the idea of 'lock-in' effects commonly found within farming, whereby farms cannot easily change between production enterprises, due to the current state of machinery and buildings, leading to a lack of flexibility for investment. A second theme emerged on the impact of cheaper inputs, such as soya feed and nitrogen, which make these methods more attractive economically and prohibit switching to inputs that may be more labour or management intensive.

Farm Characteristics: The three themes which emerged were around the capacity of the farm to 'retro-fit' a

solution to the current system and this inhibits 'outside' thinking towards what options the farm has. Secondly, the time frame to implement changes is not clear to farmers, and the constraints caused by the fixed asset base of farms, e.g. machinery replacement runs in long planning cycles. Finally, a strong theme was around the ability to make changes on the farm, as a result of tenure arrangements and land-owner restrictions, or within family constraints (in family farms) where partners or family-members may fail to agree on approaches.

Institutional conditions

Supply chains: The main themes were the influence of a particular supply chain on actual behaviours including a lack of knowledge of alternative approaches, e.g. machinery dealers may not promote more conservation-based methods, and the activities of some private agronomists to sell at volume. All this would create much more noise around the decision-maker(s) preventing them from changing their system. A second theme, related to this, was the lack of guidance and support services available for changes, and the availability of inputs, such as breeds or seeds, which would make their ability to integrate these MMs into their system easier.

Policy: A main theme emerged around policy uncertainty and a lack of long term direction of policy to support changes. Moreover, a theme emerged around policy frameworks not joining up as it crosses multiple remits, i.e. energy, telecommunications and environment. Finally, some stakeholders raised the issue of providing advisory support and guidance for complex transistions which they felt was not fully supported by Government.

Other Conditions: Several other themes emerged which are only indirectly related to the above areas. These could be summaried as: i) the current bureacracy around permanent changes in land use and the fact that to meet targets requires a fundamental system change rather than just 'tinkering' within the margins; ii) questions were raised about the ability to measure any improvements, in particular methane emissions in the field, soil organic matter (which takes around 10 years to show improvements), and iii) the effect of weather variability which can have a large effect on year to year metrics and how this may affect payment rewards but also farmer confidence that measures put in place are working.

The extended list of MMs was presented to a group of invited stakeholders at a workshop in May 2019. In total 12 of the stakeholders' consulted in the first round attended. The aim of the workshop was to categorise the mitigation measures by the main farming systems of cropping, upland, and lowland livestock (sheep and beef), and dairy systems. This was engendered through mapping the feasibility of application and impact on GHGs of each MMs. Stakeholders were asked to map: i) which measures were feasible and if not, what factors limited their feasibility, ii) which measures were considered most effective, and iii) groups were asked to consider what would enable farming system types to promote implementation of GHG mitigation. The main results are presented in the supplementary material excel spreadsheet *'Stakeholder Workshop Mapping.xls' (see outputs)*. In summary, the feasibility and choice of measures, as would be expected, differ across farm type. For cropping systems the most feasible were around the use of catch and cover crops, and keeping pH at an optimum. For livestock this differed by system, with lowland enterprises supporting better soil health measures, such as keeping pH at an optimum for plant growth (e.g. liming). For upland livestock it was felt there was less flexibility in application and the favoured measures were around improved grazing management; better species quality and diversity of in-bye land. For dairy systems the most feasible actions revolved around increasing soil organic matter. For a number of sectors woodlands were seen as potentially feasible but required nudges through fiscal incentives. Other measures could be encouraged through provision of targeted advice to make them more feasible. Overall, it was concluded that consideration of longer term planning to encourage a more inclusive and longer term system change is needed.

Farmer Workshops

A participatory mapping tool was developed for this research which helped to filter through the large range of mitigation methods, and considered both impact on GHGs and feasibility in application for each of the MMs. This allowed us to focus the workshops with farmers on a specific set of high priority mitigation measures. Six farmer workshops were undertaken to discuss feasibility and applicability, as well possible incentives for encouragement. A total of 99 farmers attended these events which were regionally focused but covered the main systems explored in this project. These are summarised in Table 1 and 2.

Table 1. Mitigation Measures for Arable Systems, colour coded to illustrate commonalities in terms feasibility across systems

	Arable- incl. Veg Crops	Arable - Combinable Crops
Easy	Improved nitrogen use efficiency using targeted release fertilisers within a farm-specific N management plan	Soil / land suitability mapping to define management /cropping choices
	Reduced intensity of cultivation	Reduced intensity of cultivation
	Increasing tree cover on farm	Reduced area of cropping systems on peat - reversion to wetland
	Reduced area of cropping systems on peat - reversion to wetland	Improved nitrogen use efficiency using targeted release fertilisers within a farm-specific N management plan
	Soil / land suitability mapping to define management /cropping choices	No bare soil - continuous-green-cover cropping systems
	Reduced use of diesel / increased renewable energy of farm	Increasing tree cover on farm
	No bare soil - continuous-green-cover cropping systems	Improving soil health
		Reduced use of diesel / increased renewable energy of farm
	Improving soil health	Farm-scale C budgeting to develop a specific C management plan
Hard	Targeted steps to increase soil organic matter	Targeted steps to increase soil organic matter

Table 2. Mitigation Measures for Beef and Sheep Systems, colour coded to illustrate commonalities in terms feasibility across systems

	Lowland B&S	Less-intensive, high ecological value	Livestock Systems including uplands
Easy	Identifying less productive areas and targeting for ecosystem services	Identifying less productive areas and targeting for ecosystem services	Increased tree cover
	Increasing tree cover on farm	Increased tree cover on farm	Identifying less productive areas and targeting for ecosystem services
	Improving soil health	Improved grazing through using diverse pastures and /or mob grazing	Improved livestock health and welfare and diet planning
	Improved grazing through using diverse pastures and /or mob grazing	Improved training for farmers and advisors	
	Improved livestock health and welfare and diet planning	Improved livestock health and welfare and diet planning	Improved training for farmers and advisors
	Site specific GHG mitigation planning	Improved soil health	
	Improved training for farmers and advisors	Site specific GHG mitigation planning	
Hard	Breeding for reduced methane reduction in cows	Breeding for reduced methane reduction in cows	Improved grazing through using diverse pastures and /or mob grazing

In terms of the uptake of MMs, the conservative approach of farmers towards planning and a lack of confidence around system change, as well as the technologies themselves, was evident. This could be related to knowledge and educational factors, resulting in a need for support to lead the change and challenge prejudices against it. Here the influence of peer-to-peer support was raised and the role that demonstration farms can play in promoting new norms for environmental engagement.

Whilst the cost-effectiveness analysis (WP1) relies on a rational economic argument which leads to adoption, there is no corresponding support for calculating on-farm investment in, relatively, untested technologies. More pertinently, the path dependancy of farms prevents a switch to a new growth trajectory for the farm. Effectively, the willingness to innovate may emerge but farmers are locked in to their current asset base. A further limit to innovation is the cheapness of some inputs, such as nitrogen and soya feed. This effectively

disincentivises any switch away from these inputs to accommodate more environmentally friendly, but potentially more inconvenient and labour intensive measures.

The tenure of the farm was raised as potentially limiting for planning in the long term, and actions such as woodland/agro-forestry are prevented due to the demands of the land owner who may be seeking to increase the value of the land for agricultural activity or maintain current payment rates for agricultural activity. It should also be remembered the farm management structures may be complex and therefore decision making is usually not in the hands of one person. In order to switch the system to something new a case may have to be made, presented and considered as the economic risk is shared.

Finally the institutions of both the public and private sector have a strong influence on the uptake of MMs. For instance, supply chains could promote carbon calculators and animal health planning as a requisite for selling produce through a particular chain. However, if the lack of guidance and support, and the availability of input materials (feeds, breed, grass seeds etc) is limited, as a result of not being promoted by local suppliers of these products, adoption of specific MMs may be impossible. In addition, the lack of coherent policy remits may also inhibit change, for instance precision farming requires elements of telecommunications and rural broadband support to encourage uptake.

Objective 3: Define feasible trajectories for English farming up to 2050 (with lessons for other UK farming communities) under 3 mitigation scenarios

Three scenarios were proposed by Defra and then refined at a stakeholder workshop held in December 2019 for policy and NGO representatives. The scenarios were:

1. A scenario which focuses solely on maximising GHG mitigation (High Mit)
2. A scenario which focuses on minimising the cost of mitigation to the sector (Low Cost)
3. A scenario which focuses on maximising wider environmental co-benefits e.g. air, water and soil quality (Co-Ben)

The baseline year for activity data was chosen as 2018 as this was the latest year with Agricultural Census data available at both the national and NUTS1 regional level. This dataset was used for cropland and grassland areas and for livestock numbers. Additional baseline datasets were applied for some other measures, such as fertilisation rates, slurry storage, food waste and agriculture on organic soils. Projected activity data for cropland and grassland areas and livestock numbers in 2050 was based on the BAU scenario, used in the work UKCEH and Rothamsted undertook for the CCC to quantify the impact of future land use scenarios (Thomson *et al.* 2018). This matches the same dataset used to develop the cost-effectiveness analysis to meet Objective 1. This dataset is for England only and the projected data for the NUTS1 regions were calculated as a fraction of the England values based on the baseline data. Projections for other activity data were similarly based on ratios of the baseline, or in some cases based on the assessments made to meet Objective 1, e.g. that household food waste would reduce by 20% by 2050.

The abatement rates for most measures were taken from the MACC (Objective 1). Where the information was available the measures were split into sub-measures depending on activity data type, e.g. cropland measures split by crop type and cattle measures split by dairy and beef. In some cases, the abatement rate was estimated through the Maximum Technical Abatement (MTP) value from the MACC with details of activity data and assumptions. For the abatement rates, the applicability, as well as the current and future uptake of measures was taken from the MACC.

Each measure was assigned a feasibility rating of: easy, medium or hard based on the assessment from the stakeholder and farmer workshops (Objective 2). Within Defra, staff from various departments were requested to comment on lead in times (number of years from 2020) and uptake for each of the measures. The uptake comments were compared to the feasibility assignment found to meet objective 2. In most cases the two were in agreement.

To model the uptake over time a logistic function was used:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}$$

Where:

L = Curve maximum (in this case maximum uptake of measure)
k = Logistic growth rate (steepness of curve)
x_0 = Value of sigmoid midpoint

The values of these parameters are defined by the scenario uptake (L = 0.3, 0.6 and 0.9 for Low, Medium and High uptake respectively), feasibility and lead in time. A curve was designed for each of the three feasibility ratings, then the lead in times and scenario uptake modify the curve for each measure. The mitigation for each scenario and region combination was calculated for the time series 2022 to 2050.

Table 3: Mitigation in 2050 for each scenario and region

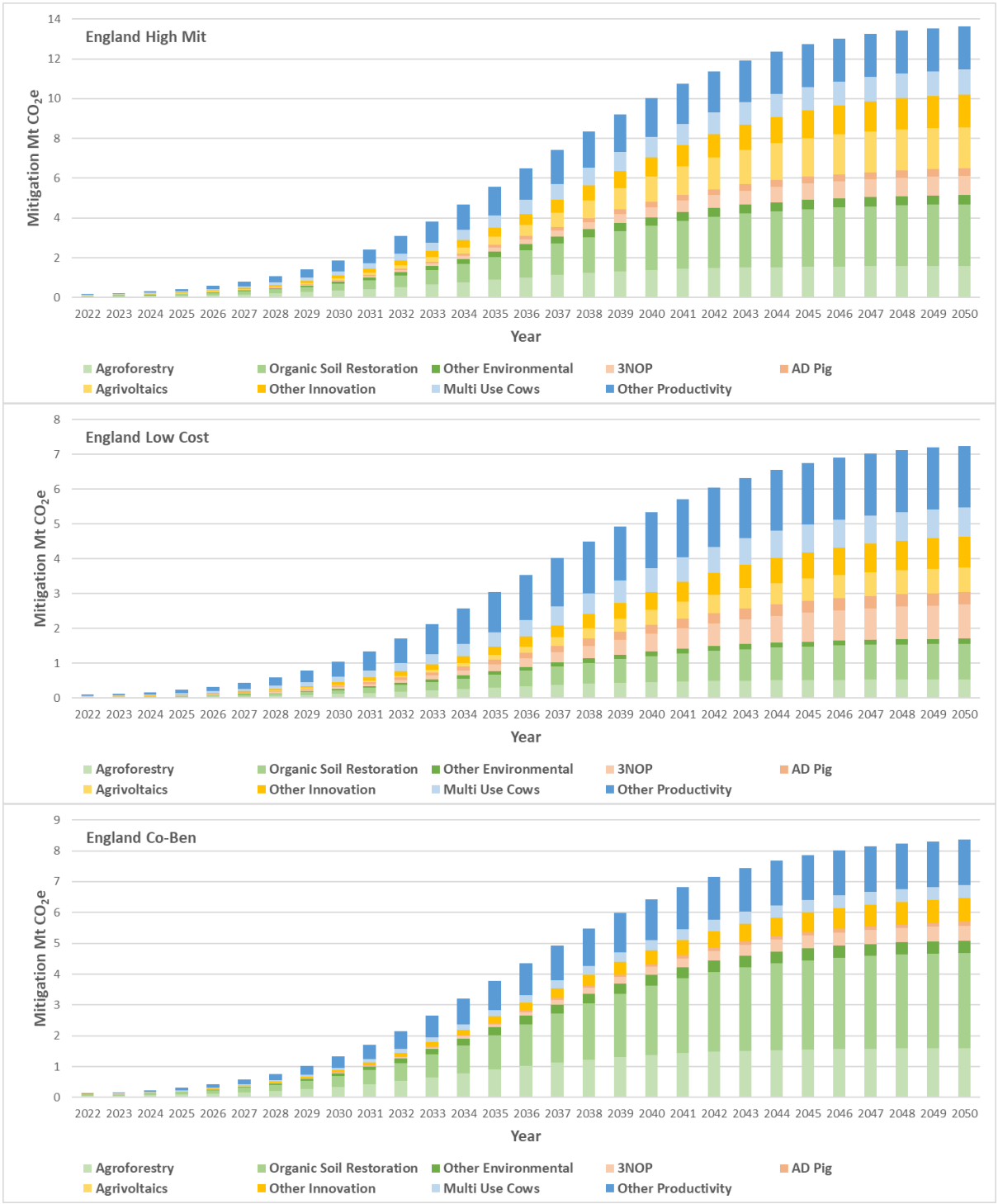
2050 Mitigation Mt CO_2e	**England**	**East of England**	**South West**	**Yorkshire & Humber**
High Mitigation	13.62	2.76	3.09	1.45
Low Cost	7.25	1.07	1.88	0.78
Co-Benefit	8.37	2.49	1.49	0.86

The magnitude of the mitigation for England can be compared to the latest published Greenhouse Gas Inventory (GHGI) figures for England (see: https://naei.beis.gov.uk/reports/reports?report_id=1000).

Under inventory reporting guidelines some of the activities encompassed by the trajectory mitigation measures would be reported under non-agriculture inventory sectors, e.g. agroforestry and OSR&P in LULUCF, biorefinery in Waste. However, for simple assessment of the mitigation trajectories we can say that High Mitigation would represent a 50% reduction in agriculture sector emissions by 2050; seeking a low cost strategy would reduce emissions by 27%, and a co-benefits strategy by 31%. Given that some of the measures can be categorised into non-agriculture areas in the inventory then these proportions should be taken as an upper bound estimate.

The MMS were assigned to one of three groups for reporting purposes: Environmental, Innovation or Productivity. The total mitigation is greatest in the High Mit scenario and least in the Low Cost scenario across all regions. However, there is variability between the scenarios and regions when comparing the measures or groups of measures. In the majority of cases the magnitude of the mitigation is dominated by three measures: Agroforestry, Organic Soil Restoration & Paludiculture (OSR&P), and Agrivoltaics. The full details and results are found in the report ‘Sustainable Intensification Trajectories’ delivered as part of this work. For brevity we show the results for England across the three scenarios,

Figure 2. Mitigation trajectories for England for the three scenarios: High Mit, Low Cost and Co-Ben. Measures are split into categories: Environmental (green), Innovation (orange) and Productivity (blue). There is zero uptake of Agrivoltaics in the Co-Ben scenario. Note the difference in scale for each scenario. Note that the estimates do not account for potential interactions between the measures which might decrease the total mitigation potential if applied together.



The extent to which these measures dominate depends on the scenario uptake rate and the relative areas of cropland, grassland and agriculture on organic soils within the region. Other measures which make up a large proportion of the mitigation are AD Pig, 3NOP and Multi Use of Cows(though the latter has high uncertainty). These measures are dependent on the scenario uptake rate and the relative numbers of cattle and pigs in the region. We classed the remaining measures as Other Environmental, Other Innovation and Other Productivity.

This objective also planned to conduct fieldwork to assess how these measures are being applied in the farm setting. The

purpose was to establish the practicalities of establishment of an approach, the effect on farm-level factors, such as labour usage and access to monitoring devices, on the feasibility of using these technologies and the possible consequences for economic and environmental indicators. However, this coincided with the Covid-19 restrictions which limited engagement directly with the industry. As an alternative it was agreed by Defra to provide a synthesis of other applied work that have examined our proposed MMs in detail. The full details are available in the Report: 'On-farm assessment of GHG mitigation implementation in practice. Case studies demonstrate positive experiences of the uptake of MMs, and should not be taken as entirely representative of farmers' universal experiences of adopting MMs.

Many of the case studies show that mitigation methods identified by the interviewer were primarily being implemented to support business development or directly to increase profitability (usually by reducing input costs) and that GHG mitigation was a welcome side-effect rather than a main driver for action. Nonetheless these farmers widely recognised the need to reduce GHG emissions as well as delivering wider environmental benefits alongside profitable food production.

Many of the farms have taken a focus on productive efficiency. Project AC0227 (ADAS UK, 2013) showed clearly that the approaches targeting energy and fuel use efficiency had a direct impact on GHG emissions that could be relatively easily measured. Farms with a focus on the efficiency of N fertiliser use (arable) and dietary planning (livestock) showed increased productive efficiency, but in Project AC0227 these changes could not be linked so directly to the GHG outcomes (both reductions and increases were modelled), but many also had wider environmental benefits.

In all the case studies it is clear that mitigation measures are not adopted singly and often their adoption is coupled with other management changes that are bundled together; this has sometimes led to major farming systems redesign e.g. the transition to dual purpose cows. There is evidence of a snowballing effect on these case study farms where the successful adoption of some technologies and techniques have been bundled with other measures or led on to adoption of a wider range of approaches, e.g. C budgeting on farm may have led to the identification and adoption of further measures. However, this is not solely (or even mainly) a result of an aspiration to achieve GHG mitigation, farmer satisfaction and well-being is an important deliverable, e.g. in increasing crop yield/quality, increasing farmland bird numbers, reducing wind blow. A common, if not always stated, theme of the case studies is that of the farmer as an agent of positive change, rather than a passive recipient of demands and requirements. This review of case studies supports the findings of ADAS UK (2013) that that the productivity impacts of implementing a GHG mitigation plan on farm are small when compared with wider farm factors. In the short-term, mitigation methods with a low capital cost show the most benefit, however, purchase of new capital equipment is sometimes manageable and even larger capital investments have been facilitated through partnerships (e.g. for agrivoltaic systems).

Many of the case studies show that there are both cost and time implications and the implementation of some mitigation methods (where more monitoring or more frequent management interventions are required) are time intensive for the farmer. However, in many of the case studies shown there is limited information on the problems in adoption and costs are not always given. Practical barriers form a large part of everyday farming operations, and it is important to appreciate that every farm is different, with its own practical barriers and it is not uncommon that farmers are unwilling to discuss these business-specific factors. Essentially, it is almost impossible to fully predict the practical barriers individual farmers will face when implementing mitigation methods, as individual circumstance may dictate a large proportion of this. In Project AC0227 (ADAS UK, 2013) practical barriers discussed by farmers ranged from small, isolated impacts such as late delivery of a piece of machinery, to large impacts which affected the whole farm business, as well as GHG emissions, such as an outbreak of livestock disease. Some practical barriers can be mitigated, such as streamlining an application process for a grant scheme funding solar panels, whilst others, such as weather impacts, are out of all control. Understanding that practical barriers will likely occur with GHG mitigation and that this may not necessarily stop farmers from pursuing the method is important.

Objective 4. Consider options for potential mechanisms for policy intervention to meet 2050 GHG goals for English farming systems (with lessons for other UK farming communities)

The suite of current policies and interventions towards uptake of sustainable agricultural methods were reviewed. This allowed us to schematically view interventions in terms of the level of choice and encouragement that may enable behavioural change. Both fiscal and non-fiscal routes can be employed depending on the complexity of the problem.

Building on the findings from the literature, an online survey was designed to elicit policy makers' knowledge

and experience regarding the suitability of the interventions for supporting mitigation methods, specifically regarding three aspects, namely i) Which type of intervention would be most effective to meet a specified target uptake rate of certain mitigation practices?; ii) What are the strengths and weaknesses of different types of interventions?, iii) Which current or currently planned policies might be used to support the mitigation actions?

In order to derive general relationships, the interventions were kept broad, grouping them in four main categories, namely:

- Regulation: current examples include the Nitrate Vulnerable Zone rules and the Silage, Slurry and Agricultural Fuel Oil (SSAFO) regulations,
- Fiscal incentives: the support of farm practices which are incentivised through payment, current examples include the CAP Greening criteria and the Environmental Stewardship schemes,
- Voluntary adoption: these will have no fiscal element but tends to rely on engagement towards a social good goal or a prevention of potential regulation, for example the voluntary pesticide initiative,
- Market-based interventions: these will be led by the market in terms of supporting adoption of methods toward carbon accounting, which leads to adoption of approaches to improve performance. An example close to agriculture is the Woodland Carbon Code.

The survey was administered across a range of Defra policy teams including agri-climate, arable and fertiliser, innovation and productivity and agroforestry amongst others. However, response rates were low which limits generalisability of the results. In response a workshop was arranged to discuss the results with a wider audience. However both the survey and the workshop were limited to Defra policy teams and therefore only represent internal commentary, the results do not necessarily represent the view of external stakeholders The table summarises the outcomes of this process. The table also presents the important attributes of the mitigation methods

Table 4. Most effective interventions to achieve the target adoption rate of the mitigation methods

Farm practice	Intervention for low target adoption	Intervention for medium target adoption	Intervention for high target adoption	On-farm net technical cost	On-farm investment cost	Feasibility of implement-tation	Ease of monitoring	Risk perceived by farmers	Applicability	Adoption level in 2020
Keeping pH at an optimum (liming)	NA	Fiscal	Regulatory	Savings	Medium	Easy	Medium	Low	Medium (grassland)	Very low
Agroforestry	NA	Fiscal	Fiscal	High	Medium	Medium	Easy	High	Very low (crop- and grassland)	Very low
Agrovoltaic systems	NA	Fiscal	Fiscal	High	High	Difficult	Easy	Medium	Very low (grassland)	Very low
Nitrification and urease inhibitors	NA	Fiscal	Regulatory	Medium	None	Medium	Medium	Medium	Medium (crop- and grassland)	Very low
Reducing soil compaction	NA	Fiscal	Regulatory	Savings	Medium	Easy	Medium	Medium	Medium (crop- and grassland)	Low
Grass-legume mixtures	NA	NA	Regulatory	Savings	Medium	Easy	Easy	Low	Very high (grassland)	Low
Restoring organic soils and paludiculture	NA	Fiscal	Regulatory	High	High	Medium	Easy	High	Medium (crop- & grassland on peat)	Very low
Anaerobic digestion of livestock manure	None	Market	Market	Savings	High	Medium	Easy	High	Low (cattle, pigs)	Very low
Breeding with genomics - current breeding goal	Fiscal	Fiscal	Fiscal	Savings	Medium	Medium	Easy	Medium	High for dairy, low for beef	Very low
Improving the health status of cattle herds	NA	None	Regulatory	Savings	None	Easy	Difficult	Low	High (cattle)	Very low
Dual purpose breeds (milk, calves and meat)	Fiscal	None	None	Savings	None	Medium	Easy	High	High (cattle)	Very low
Nitrate additives	None	Regulatory	NA	Medium	None	Medium	Medium	High	Medium (dairy cows)	Very low

Overall, an argument emerged for a mixed approach. In particular, the use of fiscal incentives initially but then raising the regulatory baseline to set sustainable practices as standard practice. Clear – and early – sight of these regulatory goals and timeframes would potentially lead to increased uptake of these fiscal incentives as a tool to engage decision-making and structural change. As a backdrop, the switch over the next decade from

basic payments to a public goods agenda effectively nudges farmers into accepting a new rationale for agricultural support from the taxpayer. Hence, the transition needs to be managed by clear messaging to encourage acceptance of a future farming industry promoting sustainable methods, which are of direct benefit to UK society. At the same time it needs to be noted that even with full adoption of these practices the total mitigation achievable would be in the range of 10-20% of agricultural emissions (Eory *et al.*, 2015) – a long way from the net zero target, creating an urgent need to speed up the decarbonisation of the food sector. In that decarbonisation - aside from changing food choices - using more land for carbon sequestration will play a very important role beside reducing the emissions from farm production (Committee on Climate Change, 2020). It should again be noted that these results are based on internal commentary from Defra policy, not necessarily reflecting external stakeholder views. The results help give an indication of what interventions may be needed to delivery varying levels of uptake to achieve the mitigation scenarios presented, but do not fully reflect those which are being developed by Defra, this work is ongoing.
Overall, this mix of intervention approaches does relate to the nature of the mitigation methods themselves. Again, this may lead to some dissonance in framing of the purpose of the intervention. The expectation would be that farmers adopt combinations of mitigation methods on farm. In the case of agro-forestry for example, which was found to be effective in both GHG and co-benefits scenarios, there would be a regulatory change, but the response would differ dependant on whether the farmer is a tenant or an owner. In the case of agrovoltaics – which also rated highly effective in the GHG scenario – energy policies will have a direct influence on the attractiveness of this approach.

Accordingly, the emphasis of the survey respondents and, more acutely, those who participated in the workshop, was around the need for messaging of the purpose of the approach to support behavioural change. Moreover, the observed dichotomy – between those who favoured regulatory compared to more voluntary fiscal approaches – may have reflected their expertise and engagement in the agricultural sector, but also highlights the effects of these differing policies on encouraging behaviour change in farming. Generally, regulation may create resistance to change but in some parts of the farming population – who have been voluntarily adopting sustainable farming techniques – it may be welcomed. Nevertheless, this is a rapidly changing market and evidence is emerging of more interest by private investors in green finance initiatives for the land use sector. The appetite for these market based initiatives by farmers may increase as these become more prevalent.

The approach of elevating adoption by reaching medium level adoption with fiscal incentives and reaching higher adoption with regulation was clearly reflected in the survey respondents' choices for four mitigation methods (liming, nitrification and urease inhibitors, reducing soil compaction and restoring organic soils), while three methods stood out as more suitable to be supported with fiscal incentives, even to achieve high adoption rates. These were the two methods which cause the biggest change in land use and cattle breeding. Interestingly, cattle health improvement attracted the suggestion of using regulatory approaches. Anaerobic digestion of manure was suggested to be achieved by market based interventions, irrespective of target adoption.

The overall appetite for market based approaches was very low in the survey and in the workshop. This might be indicative of a volunteer's dilemma, whereby the various participants in the sector (farmers, retailers, policy makers, even consumers) are waiting for each other to move towards the use of carbon benchmarking as a mechanism to acknowledge environmental improvements on the farm (and eventually link actions to payments). This may have been exacerbated by the lack of infrastructure in this area and the difficulty in creating credible and robust monitoring and verification mechanisms (Grosjean *et al.*, 2016). Notably, there has been an increased change in marketing methods

Conclusions
The analysis provided here has proven valuable in the ongoing dialogue around land use and agricultural policy as the UK withdraws from the EU and establishes its own payment mechanisms for encouraging public goods. Defra leads and research partners have engaged with BEIS on developing skills in the agricultural sector but also the CCC to help inform the 6th Annual Carbon Budget. Whilst this work has helped to support some of the dialogue as policies evolve, assessment of cost-effectiveness of on farm application has found a number of evidence gaps. In particular estimating newer technologies such as 3NOP outside of test sites, though even in well-tested practices such as agroforestry, there are uncertainties due to variances in siting and management.

Another constraint would be the attendance to workshops. Whilst we encouraged wider engagement in the

farming and the policy population there may be some biases from those who finally attended rather than being reflective of the whole community. However, for the former at least, the findings on barriers to uptake align with those from larger studies found in the literature.

The project gained and has continued to gain significant interest from policy makers at Defra, the CCC and BEIS as well as other administrations, e.g. the Scottish Government, and industry, e.g. AHDB. Throughout the project extensions have been made to the contract to extend the number of MMs reviewed in depth to meet policy interest, to explore the consequences of MMs on air quality to and develop a further scenario to explore uptake and interactions of certain measure groupings, namely agroforestry and livestock, when payment is used as an incentive.

Further work could be undertaken on a number of areas, such as understanding responses to payment mechanisms and the role of market incentives for encouraging transition as part of an environmental land management approach, and the role of skills provision and advisory services to support transition which was raised a potential topic with BEIS.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

A number of reports have been delivered through the course of this project:

Objective 1:
MM Fiches. These are a collection of detailed and in depth analysis of the MMs chosen for deeper analysis
Marginal Abatement Cost Curve with Interactions Table. This provides the abatement potential and cost effectiveness estimates for each mitigation measure, considering interactions, presented as a table.

Objective 2
'Barriers to uptake of Clean Growth Mitigation methods' This is a detailed literature review of barriers to adoption of climate related approaches.
'Mapping Farmer expectations of mitigation measures against economic feasibility' This provides a detailed report of the approaches used for engagement with stakeholders and farmers.
'Stakeholder Workshop Mapping.xls'. This presents the results of the mapping exercise with stakeholders to understand most effective and feasible technologies per main farm type.

Objective 3
'Sustainable Intensification Trajectories'. This provides the methodology and results for England and the sub-regions.
'DCGtSI_Trajectory_Results_Summary_V3.1.xlsx': this is an excel queryable data sheet with detailed trajectories.
'On-farm assessment of GHG mitigation implementation in practice'. This provides a review of case studies and synthesis of general findings towards application on-farm

Objective 4
'Opportunities for interventions to deliver greenhouse gas mitigation in England'. This details the results and approaches used examine interventions to encourage transition within English farming

Supplementary Information and Tools Developed within the Project
Agroforestry Fiche Refinement and web-based agroforestry modelling tools
Ammonia co-effects of agricultural greenhouse gas mitigation measures
Development of an additional mitigation scenario and mitigation trajectory exploring uptake and interactions between specific grouping of mitigation measures.
An R package 'ggmacc' has been developed. This supports drawing of MACC's based on cost effectiveness and abatement potential. This is available at: https://github.com/aj-sykes92/ggmacc

The project has been referenced in
The 6th Carbon Budgets for Agriculture and Land Use: https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Agriculture-land-use-land-use-change-forestry.pdf

Climate Exchange (CxC) acknowledges the project, see p6 of:
https://www.climatexchange.org.uk/media/4612/cxc-marginal-abatement-cost-curve-for-scottish-agriculture-august-2020.pdf

A series of annual meetings were convened with a focus on each work package finding. This was attended by members of Defra, the Scottish Government, BEIS and the CCC, as well as industry and NGO representatives. A final meeting in February 2021 outlined the consequences of the findings against changing English policy for support of agriculture.