Evidence review of the potential wider impacts of climate change Mitigation options: Agriculture, forestry, land use and waste sectors

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Abbreviations

AD	Anaerobic digestion
ALULUCF	Agriculture, Land Use, Land Use Change and Forestry
CGE	Computable general equilibrium
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
FTE	Full time equivalent
GHG	Greenhouse gas
IO	Input-Output
LULUCF	Land use, land use change and forestry
MO	Mitigation option
NH_3	Ammonia
N_2O	Nitrous oxide
NO_x	Mono nitrogen oxides
PM	Particulate matter
PM_{10}	Particulate matter 10 micrometres or less in diameter
$PM_{2.5}$	Particulate matter 2.5 micrometres or less in diameter
SAM	Social accounting matrix
WI	Wider impact
WTP	Willingness to pay

Executive summary

Greenhouse gas (GHG) mitigation is a central policy objective in Scotland. The Climate Change (Scotland) Act 2009 sets an interim 42% reduction target for 2020 and an 80% target for 2050 across all sectors of society (1990 baseline). As a priority policy area, it has become vital to better understand the co-benefits and adverse impacts arising from mitigation actions on our environment, economy and society. Integrated assessment is key in prioritising environmental actions, reducing adverse impacts and enhancing positive co-effects. This report aims to summarise evidence on the wider impacts (WI) of GHG mitigation options (MO) in the Agriculture, land use, land use change and forestry sectors (ALULUCF) and those related waste management. The key findings of the review, namely a summary of the wider impacts and an overview of the challenges in quantifying and monetising these impacts are presented in this section. The ALULUCF MOs and WIs assessed in this report are presented in Table 1.

Table 1 ALULUCF mitigation options and wider impacts considered in the study

Mitigation options
Developing on-farm renewable energy sources
Increased uptake of precision farming techniques
Achieving and maintaining optimal soil pH level
Anaerobic digesters for manure processing
Agroforestry
Incorporating more legumes in grass mixes/crop rotations
Optimising use of mineral nitrogen fertiliser
Low-emission storage and application of manure
Improving livestock health
Reduced livestock product consumption
Afforestation
Peatland restoration

Wider impacts
Air quality: NH_3
Air quality: NO_x
Air quality: PM
Air quality: other
Water quality: Nitrogen leaching
Water quality: Phosphorous leaching
Water quality: other
Soil quality
Flood management, water use
Land cover and land use
Biodiversity
Animal health and welfare
Crop health
Household income
Consumer and producer surplus
Employment
Resource efficiency
Human health
Social impacts
Cultural impacts

Wider impacts of the GHG mitigation options in Agriculture and LULUCF:

- Most impacts of the selected mitigation options were neutral or positive, with only a small proportion of adverse impacts.
- There is robust evidence on co-benefits deriving from all MOs, with multiple positive impacts from on-farm renewable energy, precision farming, anaerobic digestion (AD), agroforestry, optimal mineral Nitrogen use, livestock health, reduced livestock product consumption, afforestation and peatland restoration, indicating the potential for delivering robust and varied co-benefits in a wide range of policy areas. Furthermore, co-benefits were identified for all MOs, though in a number of cases the evidence was moderate or weak.
- There is also robust evidence of adverse impacts from AD in terms of mono nitrogen oxide (NO_x) emissions. Similarly for the effect of peatland restoration on water quality due to leaching of nitrogen and phosphorous, particularly in the first years of restoration.
- The effect on a number of wider impacts were variable (having both positive and negative effects in the same impact category), implying the need for specific tailored implementation which can maximise the benefits while reducing the adverse impacts. These variable effects were mostly associated with reduced livestock product consumption, afforestation, low emission storage and application of manure and peatland restoration. Variable impacts can be due to the varied technologies an MO might encompass (e.g. low emission storage and application of manure covers very different technologies), or that the effects depend on how the option is implemented (e.g. location is critical for afforestation), or that certain groups in society might experience benefits while others losses (e.g. reduced livestock product consumption).
- Evidence on the impacts of some MOs were weak, reflecting knowledge gaps, particularly in the case of reduced livestock product consumption, livestock health and optimal soil pH, low emission storage and application of manure and more legumes.
- Many MOs can have positive effects on air quality, water quality, resource efficiency and human health. Integrated approaches in these policy areas can promote these co-benefits. Crop health and cultural impacts may be affected by the lowest number of the MOs as assessed in this report,

nevertheless the magnitude or in some cases regional/local importance of these impacts calls for further investigation.

- Household income, consumer and producer surplus, employment and cultural impacts were the wider impact categories where evidence on the effects was the weakest across the MOs, calling for a research agenda which explores the synergies and trade-offs of agricultural GHG mitigation with these areas. Soil quality, human health and social impacts were the impact cateogries with the least robust evidence basis.

Quantitative aspects of impact assessment:

- There is robust modelling capacity for most of air and water quality impacts and flood management. UK specific models are available to capture both the changes in farm management and in land use related to the MOs. Existing monetary values used by UK Government can be applied the major air pollutants (ammonia (NH_3), NO_x, PM), however, these values only include some human health impacts. Existing monetary values for nitrogen pollution relate only to specific locations in Scotland, while no monetary values were found for phosphorous pollution of water. Monetary values for flood risk can be captured by existing spatially explicit property damage values.
- Soil quality modelling focuses on soil carbon, with other aspects (like hydrologic and biologic characteristics) less explored. There is a knowledge gap in estimating the quantitative impacts of MOs which affect farm management rather than land use (i.e. MO1-MO9) on soil quality. Furthermore, currently only the production effects and erosion impacts (sediment in water-bodies) of soil quality can be captured in monetary terms.
- Larger scale land use changes related to afforestation and reduced livestock product consumption can be predicted using models that represent the economic drivers and the biophysical constraints. There are no models to quantify the finer changes potentially induced by on-farm renewables and planting more legumes. Similarly, existing models are capable of estimating the biodiversity impacts of MOs resulting from land use change, but finer, farm management changes related to changes in farm management (MO1-MO9) cannot currently be assessed. Monetary values suitable for national scale assessment of biodiversity are available (they are based on the impact of habitat improvement on charismatic and non-charismatic species).

- No models or tools were found to quantify the WIs on animal health and welfare and crop health. The value of production loss impacts of animal and crop health may be captured using market values. Existing monetary values for animal welfare could not be linked to the potential welfare outcomes of the MOs assessed in this report.
- Economic models can quantify the impacts on household income, consumer and producer surplus and employment, and energy efficiency, though currently these models are more suited to assess larger scale impacts than on farm management changes.
- Modelling the impacts of human diet on health are well-developed, and air and water quality related health impacts can also be modelled with existing tools. But a number of more specific potential health effects related to some mitigation options (e.g. zoonoses and antimicrobial resistance) cannot currently be modelled. Estimates for the monetary value of human health exist and are used in UK Government policy assessments.
- Social and cultural impacts are difficult to quantify and no tools were found apart from those to quantify the recreational benefits of green space. Evidence on the monetary values of the cultural impact is limited, being based on impact of improvements to habitats on ‘sense of place’. Currently there is no evidence on the valuation of social impacts.

Waste:

- The literature reviewed indicates that as waste is moved up the hierarchy, from residual disposal and treatment to recycling, the number of people employed per tonne managed (the 'employment intensity') tends to increase.
- There are indications that the employment intensity for recycling varies by material type. The recycling of plastics and aluminium is considered in the literature to lead to some of the highest employment intensities.

1 Introduction

1.1 Background

GHG mitigation is a central policy objective in Scotland. The Climate Change (Scotland) Act 2009 sets an interim 42% reduction target for 2020 and an 80% target for 2050 across all sectors of society (1990 baseline). Annual targets are also set by legislation, along with a report on policies and proposals for meeting the annual targets. Agriculture, land use and land use change and forestry (ALULULCF) and waste sectors have important roles to play in contributing to Scotland's emission reduction targets. Between 1990 and 2014 agriculture's emissions have reduced by 14%, waste emissions have reduced by 77% and carbon sequestration by the land use and land use change and forestry sector has increased by 3.9 Mt CO_2e (carbon dioxide equivalent), based on solely territorial emissions (not taking account of the GHG impacts associated with the production of materials produced overseas).[1] However, further mitigation in these sectors will be required to achieve Scotland's 2050 emission reduction target.

Long-term sustainability requires finding a balance in our environmental, economic and social goals, taking into account the resources used in meeting these. This is complicated by potential and actual synergies or trade-offs between the sustainability goals and by the differences in how society and individuals value these goals. The final impacts on human well-being happen through a complex network of environmental, economic and social pathways.

As GHG mitigation has become one of the highest priority areas, it has become vital to understand the co-benefits and adverse impacts arising from such actions on our environment, economy and society (IPCC 2014). Adopting a multi-objective perspective can help to identify areas where synergies make policies more robust and to mitigate the adverse impacts of policies which impose trade-offs.

Land use related activities can be particularly challenging because of multiple, often conflicting societal needs. A prime example is land use itself, as it provides food, fuels, area for human settlements and environmental benefits. Biological and chemical processes result in further need to consider trade-offs, for example reducing one particular form of reactive nitrogen (e.g. NH_3) might cause an

[1] Figures are consistent with those set out in the Climate Change Plan

increase in other forms of reactive nitrogen pollution (e.g. NO_x or nitrogen leaching) (Sutton ed. 2011).

Integrated assessments require the consolidation of the various environmental and economic processes and a framework to evaluate the potential solutions against each other. For most such frameworks the ultimate end-point are the human welfare effects, which are quantified by translating the physical effects (e.g. NH_3 pollution or human health effects) into monetary terms. Though difficult to obtain, such estimates already exist in relation to certain wider impacts and are important in impact assessment.

1.2 Research aims

As the Scottish Government further develops policies and proposals to increase GHG mitigation across society, a better understanding of the potential wider impacts of these is needed, along with developing an overview of potential co-benefits and adverse side effects of policy, and of how key synergies and trade-offs can be quantified. To support this work in the ALULUCF and waste sectors, Scottish Government identified the following research questions:

1. What is the evidence, both quantitative and qualitative, of potential wider impacts (co-benefits and adverse side effects) for Scotland arising from climate change mitigation actions which would be relevant to the Scottish context?
2. Based on a review and synthesis of quantitative evidence, which models and tools are assessed as the most robust to quantify and, where possible, monetise such wider impacts? What quantitative data would be required to apply these models to Scotland? What key assumptions are required?
3. Based on a review and synthesis of qualitative evidence, what are the key sources of robust evidence; and what is the balance of evidence, in terms of the direction (positive / negative) and potential magnitude, of those wider impacts relevant to Scotland?
4. From an equalities perspective, what evidence is there about the potential distribution of wider impacts relevant to Scotland across the population?
5. What are the most significant gaps in research and evidence about potential wider impacts which are relevant to Scotland?

The most important questions for the Scottish Government regarding the waste sector were slightly different from the other sectors; two aspects of the wider impacts of GHG mitigation in the waste sector were considered, as requested from the Scottish Government:

1. Employment benefits from diverting increased tonnages from landfill to recycling: an evidence review of the potential employment benefits (taking into account job displacement) from diverting tonnages from landfill to recycling. Is there any evidence for different sized benefits depending on the type of waste?
2. Evidence review of the potential magnitude of non-territorial emission savings as a result of meeting the Scottish Government's waste targets and a review of the potential approaches to assess the non-territorial emission savings.

This report considers the WIs of MOs in ALULUCF and waste sectors in Scotland. It provides an overview of the direction and magnitude of these impacts and considers appropriate models and tools for quantitative evaluation. A second objective is to summarise evidence on the monetary valuation of impacts in order to facilitate integrated assessment. The report also highlights further research needs in exploring the synergies and trade-offs arising from GHG mitigation in Scotland.

The report is structured as follows. Section 2 sets out the methodology, explaining how the MOs were selected and what wider impacts were considered. Section 3 summarises the key messages regarding the wider impacts, their modelling and valuation in the ALULUCF sectors – more details of these issues are provided in Appendix A1, Appendix A2 and Appendix A3. Section A1.1 describes the findings of the qualitative evidence review in the waste sector.

2 Approach to the evidence review

2.1 Selection of mitigation options

There is a wide variety of potential GHG MOs within the ALULUCF sector. For example, the 2015 GHG marginal abatement cost curves for agriculture (Eory *et al.* 2015) identified 26 potential measures for Scottish farming. For the current report to add most value it was agreed that the evidence review would focus on a selection of MOs. Following discussion with the Scottish Government and after taking into consideration the 2015 GHG marginal abatement cost curves for agriculture, independent expert advice received by the Scottish Government and a recent Department for Energy and Climate Change commissioned report (Smith et al, 2017) into wider impacts of climate change MOs, the following twelve MOs were selected.

Table 2 Mitigation options assessed

	Mitigation Option	Brief Description
MO1	Developing on-farm renewable energy sources	Land managed on Scottish farms often has excellent renewable energy potential, and renewables are an important part of Scotland’s effort to reduce GHG emissions.
MO2	Increased uptake of precision farming techniques	Precision farming includes management practices and a range of technologies enabling farmers to analyse information on soil, crop and animal quality. This can contribute to reducing energy use by machinery, and/or the GHG emission intensity of crop and livestock products.
MO3	Achieving and maintaining optimal soil pH level (grassland and arable land)	The Scottish Government are in the planning stages of introducing compulsory soil testing on improved agricultural land. This should give farmers the tools to understand and manage their soil and could help reduce over-application of fertiliser while simultaneously increasing farm profitability.
MO4	Anaerobic digesters for manure processing (community AD facilities of around 750KW – 1 MW)	AD of manure can reduce methane (CH_4) emissions from storage and can provide alternative energy sources, thus providing further, indirect, GHG savings.
MO5	Agroforestry	Agroforestry can sequester carbon and also enable farms to provide a range of ecosystem services while having little or no negative effect on food production.
MO6	Incorporating more legumes in grass mixes/crop rotations	Legumes have symbiotic relationships with bacteria allowing them to fix atmospheric nitrogen and use this in place of nitrogen provided by synthetic fertilisers. They are also supply nitrogen to crops they are mixed with (e.g. clover-grass mixtures) and to subsequent crop

	Mitigation Option	Brief Description
		rotations (e.g. peas in one year and cereals in the next).
MO7	Optimising use of mineral nitrogen fertiliser	Optimising the use of mineral fertiliser means that the fertiliser will be used more efficiently, thus reducing application rates.
MO8	Low-emission storage and application of manure	This approach can reduce NH_3 (providing savings in indirect N_2O emissions) and CH_4 emissions, and can result in retaining more nutrients for target crops.
MO9	Improving livestock health	Livestock diseases can lead to impacts on livestock performance. Treating and preventing diseases tend to increase productivity and lead to decreases in the emissions intensity of the meat, milk or eggs.
MO10	Reduced livestock product consumption	Positive health impact of a dietary shift from meat-consumption could be the single largest co-benefit of any GHG-mitigating measure examined. Evidence indicates combined GHG and health benefits warrants further investigation of WIs.
MO11	Afforestation	Afforestation is potentially a major contributor to reducing the net GHG emissions by sequestering carbon in the soil and as woody biomass.
MO12	Peatland restoration	Peatland restoration can reduce the carbon dioxide (CO_2) emissions associated with the degradation of soil carbon content in peatlands that have been (partially) drained.

As agreed with the Scottish Government a different approach has been taken in reviewing the wider impacts associated with the waste sector. For this sector attention has focused on potential employment benefits from diverting tonnages from landfill to recycling, with a high level consideration of non-territorial emissions.

2.2 Wider impacts and the impact pathway

The wider impacts associated with GHG mitigation in the ALULUCF and waste sectors are many and varied. Likewise, the pathway through which these co-benefits and adverse side-effects arise can be complex. For example, a MO can have a wide range of direct effects, such as impacting on NH_3 levels or the level of nitrogen leaching. These primary effects can then translate into intermediate impacts i.e. changes in air quality and water quality respectively, which in turn can lead to impacts on human well-being (endpoint impacts), such as changes in human health.

An understanding of the different pathways through which MOs can have wider impacts is important in the development of policies. Once the pathways are identified policies can be designed to maximize the co-benefits and mitigate the adverse side-effects.

This evidence review has found that the majority of qualitative evidence focuses on the direct effects, but ultimately the monetary values of impacts are directly related with endpoint impacts. However, the relation between direct impacts and end-point impacts is not of a one-to-one identity: direct impacts contribute to multiple intermediate impacts that in turn contribute to multiple end-point impacts. Conversely, changes in various aspects of human well-being (e.g. human health or cultural well-being) depend on multiple primary impacts. Disentangling these complexities and quantitatively attributing the end-point or intermediate impacts to direct impacts is often unfeasible, but certain parts of these pathways are becoming well- described.

As direct evidence on the wider impacts or agricultural production practices is mostly available at the direct impact level, the main focus of the report was placed on these impacts. For some of these impacts some level of monetary valuation is already available. The **direct impacts** considered were **NH_3, NO_x, PM, nitrogen and phosphorous** as the main agriculture-related drivers of air and water quality, ultimately impacting on agricultural production, human health and biodiversity; **water use**; **animal health and crop health**, which have downstream impact on food production; **animal welfare** (contributing to spiritual well-being); **land cover and land use**, which has wide-ranging impacts on agricultural production, biodiversity, flood regulation, human health and spiritual wellbeing; and the economic and social primary impact of **income, consumer and producer surplus and employment**.

Four **intermediate impacts** were also included in the assessment: **soil quality, flood regulation, biodiversity and resource efficiency.** Considering soil quality, flood regulation and biodiversity instead of the direct impacts driving them (e.g. soil carbon content, soil moisture, land cover, air and water quality) is more suitable due to the available monetary values and valuation methodologies. The biodiversity impacts are considered only at the local scale, i.e. direct impacts in local biodiversity, rather than off-site impacts mediated through changes in air quality or water quality. Resource efficiency is a highly aggregated wider impact including material use, like nitrogen, phosphorous, water, and energy use. This was added as a wider impact to help the alignment of the findings with the Scottish Government's circular economy aspirations.

Finally, three **endpoint impacts** were also included. **Human health** was explicitly considered as the food consumption demand side MO has a strong impact on it, which cannot be captured looking at impacts upstream in the pathway. The scarcity of evidence on impacts related to **social and cultural** wellbeing suggested an aggregate assessment at the endpoint level. Endpoint impacts are the highest level of aggregation, and as such, they include wide-ranging issues, restricting the level of detail in the assessment, but still providing some guidance on the direction of impacts.

Table 3 Wider impacts considered

	Wider impact	Type of impact
WI1	Air quality: NH_3	Direct
WI2	Air quality: NO_x	Direct
WI3	Air quality: PM	Direct
WI4	Air quality: other	Direct
WI5	Water quality: Nitrogen leaching	Direct
WI6	Water quality: Phosphorous leaching	Direct
WI7	Water quality: other (e.g. pesticides)	Direct
WI8	Soil quality	Intermediate
WI9	Flood management, water use	Intermediate /Direct
WI10	Land cover and land use	Direct
WI11	Biodiversity	Intermediate
WI12	Animal health and welfare	Direct
WI13	Crop health	Direct
WI14	Household income (income effects and distribution of impact)	Direct
WI15	Consumer and producer surplus	Direct
WI16	Employment (type and number of jobs)	Direct
WI17	Resource efficiency	Intermediate
WI18	Human health	Endpoint
WI19	Social impacts (cohesion, social engagement)	Endpoint
WI20	Cultural impacts (recreation, spiritual, cultural heritage, landscape value)	Endpoint

2.3 Methodology

This study used a rapid evidence review methodology, consisting of a literature review, which included peer-reviewed publications and grey literature (reports produced by national, international and third party organisation). International literature was considered for its applicability in a Scottish context. Where direct evidence was not available expert judgement was used, stating the likely importance of the WI.

The summarised evidence attempts to cover the most important aspects of the GHG MOs, highlighting trade-offs and synergies without covering the finer details of spatial and temporal variations or the heterogeneity of biophysical constraints or agricultural management; all of which might change the magnitude or direction of the impacts. However, significant dependencies of this kind are highlighted in the report.

Some MOs cover a range of different practices on farms (e.g. renewable energy, low emission storage and application of manure, improving livestock health). Here general impacts are presented noting the key specific impacts. Similarly, the WIs are often composites of very varied impacts; for example cultural impacts include recreational, educational, spiritual and aesthetic aspects. The assessment of these WIs offers a high level overview, with highlight of specific issues (e.g. the recreational impact of afforestation is discussed in more detail).

Beyond providing a short explanation on the processes resulting in the WIs in relation to the MOs, each WI of each MO is scored at a 5-level scale (from strong positive to strong negative effect), while the evidence available was rated as weak, moderate or robust.

The MOs and the WIs are not directly comparable at an aggregated level based on the presented results, i.e. a MO with three positive effects is not necessarily more desirable than another MO with two positive effects (all other things being equal). This is at one hand because a 5-level scale can only distinguish positive and strong positive effect, meaning that there can be considerable difference between two impacts assessed equally. More importantly, the assessment only considers the physical impacts without converting these to impacts on human well-being. Additionally, as the WIs evaluated relate to different impact-levels, the interrelations between them (e.g. NH_3 emissions having an impact on human health) means that some aspects are considered more than once in the qualitative assessment. This double counting should be avoided before any aggregated quantitative analysis to be done.

Available tools for the assessment of the WIs in relation to the MOs were also reviewed, providing short description of models and tools that could (or have been) used to assess the WIs at the national level.

3 Potential wider impacts GHG mitigation in agriculture, land use, land use change and forestry

3.1 Qualitative evidence

Table 4 provides an overview of the wider impacts of the GHG mitigation options (detailed narratives can be found in Appendix A1 and Appendix A2). The scores show the direction and magnitude of impact (positive denoting favourable impact) and the colour scale provides an assessment of the robustness of the available scientific evidence (weak evidence refers to situations where there is limited availability of evidence and/or there are conflicting findings, while robust evidence refers to conclusive evidence). The majority of the WIs were positive or neutral, with also a high number of variable impacts (i.e. positive and negative impacts both possible), but there are no strongly negative impacts.

There is evidence on co-benefits potentially arising from all MOs. Multiple robust co-benefits are related to from on-farm renewable energy, precision farming, AD, agroforestry, optimal mineral N use, livestock health, reduced livestock product consumption, afforestation and peatland restoration, indicating the potential for delivering co-benefits in a range of policy areas. Strong and robust positive effects were found for AD on resource efficiency, low emission manure storage and application on NH_3 emissions, reduced livestock product consumption on human health, afforestation on air quality and on flood management and peatland restoration on soil quality and biodiversity.

Adverse impacts were associated with eight MOs, though evidence on some of these was limited and therefore the impacts are uncertain. Negative impacts with moderate or robust evidence were found for on-farm renewables, AD, improving livestock health, reduced livestock product consumption, afforestation and peatland restoration. On-farm renewables can have a small unfavourable impact on land use by occupying areas could be used for other purposes. Anaerobic digesters produce air pollutants (NO_x and PM) in the combustion process. Improving livestock health might negatively affect biodiversity if habitats are altered to reduce vector borne diseases (e.g. field drainage to reduce mud snail populations, which act as a vector for liver fluke) and also from certain medications released to the environment via livestock excreta. Reduced livestock product consumption might lead to increased pesticide use due to higher vegetable consumption. Afforestation might result in increased tick populations near grazing livestock, increasing the risk of tick-borne diseases. Finally, increased nitrogen and phosphorous leaching is possible in the first years of peatland restoration. Careful planning and implementation are needed to minimize these effects.

Several impacts were variable, calling for specific implementation to maximise the benefits while reducing adverse impacts. These variable effects were mostly associated with reduced livestock product consumption, afforestation, low emission storage and application of manure and peatland restoration. In most of these cases the reason behind the variable impact was that either the MO or the WI is an aggregation of varied technologies or impacts, respectively. For example low emission storage and application of manure includes various technologies related to manure storage and manure spreading; these technologies have different effects on the environment. In other cases the effects on a WI greatly depends on the particularities (e.g. location, species, management, ownership) of implementation, for example covering the digestate from AD can mitigate the otherwise increased NH_3 emissions, and the location of afforestation and peatland restoration projects can define whether the cultural effect is positive or negative.

The most uncertain MOs (i.e. those MOs with the highest number of WIs supported only by weak or moderate evidence) were reduced livestock product consumption, livestock health and optimal soil pH, and, to a lower extent, low emission storage and application of manure and more legumes. On the other hand, WI's related to afforestation and optimal use of mineral nitrogen seemed to be the best explored. This is to be expected for the former three MOs, as research has relatively recently started focusing on their GHG effects (either globally, like reduced livestock product consumption and livestock health, or in the Scottish context, like optimal soil pH). Further research could help in closing these knowledge gaps. Highlighted areas are soil pH impacts on water quality, soil quality and biodiversity, the influence of improving livestock health on pesticides and human health, and the effects of reduced livestock product consumption on the structure of agricultural production with particular emphasis on soil quality, biodiversity, animal health and welfare, employment, social and cultural impacts.

Many MOs can have co-benefits in relation to air and water quality, resource efficiency and human health, and these co-benefits can be promoted by integrated approaches in these policy areas. The WIs that had the highest number of variable co-effects were soil quality, flood management and water use, household income and human health. Again, policy integration of these areas and GHG mitigation is key in maximising the net benefits.

The impact categories least affected by the MOs considered air quality other than NH_3, NO_x or PM, cultural impacts and crop health (four to five MOs impacting on any one of them). However, the magnitude of these impacts emphasises the importance of integrated approaches. For example, the cultural impacts of afforestation or peatland restoration requires the consideration of both environmental and social aspects in planning and management, and the likely impact of agroforestry on crop health calls for developing capacity to incorporate crops pest and diseases assessment in local and regional decisions on agroforestry.

Four WIs were found to be the most uncertain (i.e. with the highest number of MOs with weak or moderate evidence on these impacts): household income, consumer and producer surplus, employment and cultural impacts. On average the environmental impacts were more robust, with the least uncertainty around NH_3 and NO_x emissions and resource efficiency.

Table 4 Summary of the WIs of the GHG MOs

		WI1 Air quality: NH3	WI2 Air quality: NOx	WI3 Air quality: PM	WI4 Air quality: other	WI5 Water quality: N leaching	WI6 Water quality: P	WI7 Water quality: other	WI8 Soil quality	WI9 Flood mgmt, water use	WI10 Land cover and land use	WI11 Biodiversity	WI12 Animal health and welfare	WI13 Crop health	WI14 Household income	WI15 Consumer and producer surplus	WI16 Employment	WI17 Resource efficicency	WI18 Human health	WI19 Social impacts	WI20 Cultural impacts
MO1	On-farm renewables	0	+	+	+	0	0	0	+/-	0	-	0/-	0	0	+	+/-	+	+	+/-	+	0
MO2	Precision farming	+	+	+	+	+	+	+	+	+	0	+	+/-	+	+	+	-	+	+	+/-	0
MO3	Optimal soil pH	+/-	0	0	0	+	+	+	+	+/-	0	+/-	+	+	+	+	0	0	+	0	0
MO4	Anaerobic digesters	-/0	-	-	0	+/-	-	0	+/-	0	0	0	0	0	+	+	+	++	+/-	+	0
MO5	Agroforestry	+	+	+	0	+	+	+	+	+	+	+	+	+	0	0	0	0	+	0	+
MO6	More legumes	+	+	+	0	-	0	0	+	0	+	+	0	+	0	0	0	+	0	0	0
MO7	Optimal mineral N use	+	+	+	0	+	+	0	0	0	0	0	0	0	0	0	0	0	+	0	0
MO8	Manure storage and application	++	0	+	+/-	+	+	+	+/-	0	0	0	+	0	+/-	0	+	+/-	+/-	0	0
MO9	Livestock health	+	0	0	0	+	+	-	0	0	0	-	+/-	0	0	0	0	+	+/-	0	0
MO10	Reduced livestock product consumption	+	0	0	0	+	+	-	+/-	+/-	+	+/-	+/-	0	+/-	+/-	+/-	+	++	+/-	+/-
MO11	Afforestation	++	++	++	+	+	0	+/-	+/-	++	+	+/-	-	0	+/-	+/-	+/-	+	+	+	+/-
MO12	Peatland restoration	0	0	+	0	-	-	+/-	++	+/-	+/-	++	+	-	+/-	0	0	0	+/-	+	+/-

Legend	
++	Strong positive effect
+	Positive effect
0	No siginificant effect
+/-	Variable effect
-	Negative effect
--	Strong negative effect
	Weak evidence
	Moderate evidence
	Robust evidence

3.2 Quantitative aspects: models and tools and valuation

MO implementation typically involves trade-offs and synergies with other policy goals. Evidence is required to evaluate these and to identify how impacts are attributable to different policies. Modelling the potential impacts is an important part of such an exercise, along with establishing the monetary values of the WIs to serve as a common metric between them.

This section summarises the modelling capacity for capturing the particular effects of the individual MOs on the WIs and the available monetary values. Model suitability is summarised in Table 5 – Table 9. The list of the WIs where currently robust valuation is available is presented in Table 10, a full list with monetary values can be found in Table 59. More detailed model and monetary value descriptions are provided in Appendix A2 and A3, respectively.

There is widely applied modelling capacity for most of air and water quality aspects. UK-specific models are available to estimate most of the air and water quality effects of changes in farm management and changes in land use related to the MOs. No suitable models were found for some water quality aspects (e.g. heavy metal pollution effects of optimal soil pH and faecal microorganism effects of low emission manure storage and application). Monetary values (used by the UK Government) are available for the major air pollutants (NH_3, NO_x, PM), however, these only include health impacts of secondary PM formation, and do not account for other health impacts or any environmental impact (e.g. acidification, eutrophication). Some monetary values exist for water quality impacts from nitrogen pollution and general water quality status (the former is location specific). No monetary values were found for phosphorous pollution of water.

Soil quality modelling is overwhelmingly soil carbon modelling, since this is an important component of structure quality. Other aspects of soil quality are not normally included in the relevant models (for example physical and hydrologic), making it unfeasible to estimate the quantitative impacts of some MOs (Anaerobic digesters, More legumes, Manure storage and application) on Soil quality. The valuation of soil quality is possible through the impacts on agricultural productivity (i.e. using market values).

The expected impacts of MOs on flood management and water use can be quantitatively assessed with hydrological models. On the valuation side existing spatially explicit property damage values can be used to value flood risk.

Larger scale land use changes related to afforestation and reduced livestock product consumption can be predicted using models (e.g. econometric or agent based models), which capture the economic drivers (subsidies, markets) and the biophysical constraints of land use. No models were found to quantify the changes potentially induced by on-farm renewables and more legumes.

Existing models are capable of estimating the biodiversity impacts of MOs which result in land use change (reduced livestock product consumption, afforestation and peatland restoration), but farm management changes (related to MO1-MO9) cannot currently be assessed. Monetary values for biodiversity are based on the way habitat improvements change the status of charismatic and non-charismatic species.

No models or tools were found to quantify the WIs on Animal health and welfare and crop health. If quantitative estimates were available, the value of the animal and crop health effects could be captured by the production changes. Existing animal welfare monetary values relate to livestock systems (e.g. free range versus caged) and cannot be linked to welfare outcomes and therefore to the management changes implied by the MOs assessed in the report.

Economic models (e.g. computable general equilibrium (CGE) models, Input-Output (IO) models and Social Accounting Matrix (SAM)) can quantify three WIs (Household income, Consumer and producer surplus and Employment and part of Resource efficiency). But these are more suited to assess larger scale impacts than those occurring at the farm scale.

For human health, dietary models are well-developed, as are those relating health to air and water quality related impacts. . But a number of more specific health effects cannot be currently modelled including zoonoses and antimicrobial resistance. There are existing estimates for the monetary value of some human health impacts.

Social and cultural impacts are difficult to quantify and no models or tools were found apart from those to quantify the recreational benefits of green space. Evidence is also limited on the monetary values of the cultural impact; existing values are based on improvements to habitats on ‘sense of place’. Currently there is no evidence on the valuation of social impacts.

Table 5 Models for air quality assessment (WIs 1-4, see model description in Appendix A2)

		WI1	WI2	WI3	WI4
		Air quality: NH3	Air quality: NOx	Air quality: PM	Air quality: other
MO1	On-farm renewables	No impact expected	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM
MO2	Precision farming	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM Farmscoper	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM	EMEP4UK GAINS/UKIAM
MO3	Optimal soil pH	EMEP4UK GAINS/UKIAM	No impact expected	No impact expected	No impact expected
MO4	Anaerobic digesters	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM	EMEP4UK GAINS/UKIAM	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM	No impact expected
MO5	Agroforestry	DNDC MODASS-THETIS EMEP4UK GAINS/UKIAM	EMEP4UK GAINS/UKIAM	EMEP4UK GAINS/UKIAM	No impact expected
MO6	More legumes	EMEP4UK GAINS/UKIAM Farmscoper	EMEP4UK GAINS/UKIAM	EMEP4UK GAINS/UKIAM	No impact expected
MO7	Optimal mineral N use	EMEP4UK GAINS/UKIAM Farmscoper	EMEP4UK GAINS/UKIAM	EMEP4UK GAINS/UKIAM	No impact expected
MO8	Manure storage and application	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM Farmscoper	No impact expected	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM	EMEP4UK (regional) SCAIL (local) GAINS/UKIAM
MO9	Livestock health	EMEP4UK GAINS/UKIAM Farmscoper	No impact expected	No impact expected	No impact expected
MO10	Reduced livestock product consumption	EMEP4UK GAINS/UKIAM	No impact expected	No impact expected	No impact expected
MO11	Afforestation	FOREST-DNDC MODDAS-THETIS	EMEP4UK GAINS/UKIAM	EMEP4UK GAINS/UKIAM	EMEP4UK GAINS/UKIAM
MO12	Peatland restoration	No impact expected	No impact expected	No models/tools found	No impacts expected

Table 6 Models for water and soil quality assessment (WIs 5-8, see model description in Appendix A2)

		WI5	WI6	WI7	WI8
		Water quality: Nitrogen leaching	Water quality: Phospho-rous	Water quality: other	Soil quality
MO1	On-farm renewables	No impact expected	No impact expected	No impact expected	Windfarm carbon calculator (wind turbines). CARBINE (biomass fuel crops)
MO2	Precision farming	LUCI, ADAS Wales, Farmscoper, NIRAMS	LUCI, ADAS Wales, Farmscoper	LUCI (sediment), ADAS Wales (pesticides), Farmscoper (pesticides)	Spacsys
MO3	Optimal soil pH	LUCI	LUCI	No models/tools found	Century
MO4	Anaerobic digesters	ADAS Wales, Farmscoper, LUCI, NIRAMS	LUCI, ADAS Wales, Farmscoper	No impact expected	No models/tools found
MO5	Agroforestry	DNDC, LUCI, NIRAMS	DNDC, LUCI, ADAS Wales	LUCI (sediment), ADAS Wales (pesticides), Farmscoper (pesticides)	DNDC, CARBINE (soil carbon stocks)
MO6	More legumes	Farmscoper, NIRAMS	No impact expected	No impact expected	No models/tools found
MO7	Optimal mineral N use	LUCI, ADAS Wales, Farmscoper, NIRAMS	LUCI, ADAS Wales, Farmscoper	No impact expected	No impact expected
MO8	Manure storage and application	ADAS Wales, Farmscoper, LUCI, NIRAMS	LUCI, ADAS Wales, Farmscoper	No models/tools found	No models/tools found
MO9	Livestock health	ADAS Wales, Farmscoper, LUCI	LUCI, ADAS Wales, Farmscoper	ADAS Wales (veterinary medicines)	No impact expected
MO10	Reduced livestock product consumption	LUCI, ADAS Wales, Farmscoper, NIRAMS	LUCI, ADAS Wales, Farmscoper	ADAS Wales (veterinary medicines)	DNDC, CARBINE (soil carbon stocks)
MO11	Afforestation	LUCI, NIRAMS	No impact expected	No models/tools found	CARBINE (soil carbon stocks)
MO12	Peatland restoration	LUCI	LUCI	No models/tools found	LULUCF Inventory (soil carbon stocks)

Table 7 Models for assessing flood management and water use, land cover and land use, biodiversity and animal health and welfare (WIs 9-12, see model description in Appendix A2)

		WI9	WI10	WI11	WI12
		Flood management, water use	Land cover and land use	Biodiversity	Animal health and welfare
MO1	On-farm renewables	No impact expected	No models/tools found	No models/tools found	No impact expected
MO2	Precision farming	IHMS, SALTMED	No impact expected	No models/tools found	No models/tools found
MO3	Optimal soil pH	IHMS, SALTMED	No impact expected	No models/tools found	No models/tools found
MO4	Anaerobic digesters	No impact expected	No impact expected	No impact expected	No impact expected
MO5	Agroforestry	IHMS, SALTMED, LUCI	LULUCF Inventory	SNH's IHN, Eco-Serve GIS, InVEST, AgBioscape, LUCI	No models/tools found
MO6	More legumes	No impact expected	No models/tools found	AgBioscape, SRUC's Biodiv Calc, InVEST, Eco-Serve GIS	No impact expected
MO7	Optimal mineral N use	No impact expected	No impact expected	No impact expected	No impact expected
MO8	Manure storage and application	No impact expected	No impact expected	No impact expected	No models/tools found
MO9	Livestock health	No impact expected	No impact expected	No models/tools found	No models/tools found
MO10	Reduced livestock product consumption	IHMS, SALTMED	Spatial econometric and agent based models	SRUC's Biodiv Calc, AgBioscape	No models/tools found
MO11	Afforestation	IHMS	Spatial econometric and agent based models, LULUCF Inventory	SNH's IHN, Eco-Serve GIS, InVEST, AgBioscape	No models/tools found
MO12	Peatland restoration	IHMS, SALTMED	LULUCF Inventory	SNH's IHN, SRUC's Biodiv Calc, Eco-Serve GIS, InVEST	No models/tools found

Table 8 Models for assessing crop health, household income, consumer and producer surplus and employment (WIs 13-16, see model description in Appendix A2)

		WI13	WI14	WI15	WI16
		Crop health	Household income	Consumer and producer surplus	Employment
MO1	On-farm renewables	No impact expected	IO/SAM, CGE	IO/SAM, CGE	IO/SAM, CGE
MO2	Precision farming	DSSAT/APSIM	CGE	CGE	CGE
MO3	Optimal soil pH	DSSAT/APSIM	CGE	CGE	No impact expected
MO4	Anaerobic digesters	No impact expected	IO/SAM, CGE	IO/SAM, CGE	IO/SAM, CGE
MO5	Agroforestry	No models/tools found	No impact expected	No impact expected	No impact expected
MO6	More legumes	ROTOR, LUSO	No impact expected	No impact expected	No impact expected
MO7	Optimal mineral N use	No impact expected	No impact expected	No impact expected	No impact expected
MO8	Manure storage and application	No impact expected	CGE	No impact expected	CGE
MO9	Livestock health	No impact expected	No impact expected	No impact expected	No impact expected
MO10	Reduced livestock product consumption	No impact expected	IO/SAM, CGE	IO/SAM, CGE	IO/SAM, CGE
MO11	Afforestation	No impact expected	IO/SAM, CGE	IO/SAM, CGE	IO/SAM, CGE
MO12	Peatland restoration	No models/tools found	IO/SAM, CGE	No impact expected	No impact expected

Table 9 Models for assessing resource efficiency, human health, social impacts and cultural impacts (WIs 17-20, see model description in Appendix A2)

		WI17	WI18	WI19	WI20
		Resource efficiency	Human health	Social impacts	Cultural impacts
MO1	On-farm renewables	AgRECalc, AGRILCA	See air quality models	No models/tools found	No impact expected
MO2	Precision farming	AgRECalc, AGRILCA	See air and water quality models	No models/tools found	No impact expected
MO3	Optimal soil pH	No impact expected	No models found for assessment	No impact expected	No impact expected
MO4	Anaerobic digesters	AgRECalc, AGRILCA	See air and water quality models	No models/tools found	No impact expected
MO5	Agroforestry	No impact expected	See air and water quality models	No impact expected	No models/tools found
MO6	More legumes	AgRECalc, AGRILCA	No impact expected	No impact expected	No impact expected
MO7	Optimal mineral N use	No impact expected	See air and water quality models	No impact expected	No impact expected
MO8	Manure storage and application	AgRECalc, AGRILCA	No models found for acid risk assessment; also see air and water quality models	No impact expected	No impact expected
MO9	Livestock health	AgRECalc, AGRILCA	No models found for zoonosis and antibiotic risk assessment; also see air and water quality models	No impact expected	No impact expected
MO10	Reduced livestock product consumption	IO/SAM, CGE	DIETRON, PRIME	No models/tools found	ORVal
MO11	Afforestation	IO/SAM, CGE	Effects of forest-related exercise on health: no models; also see air and water quality models	No models/tools found	ORVal
MO12	Peatland restoration	No impact expected	No models/tools found	No models/tools found	ORVal

Table 10 Robust monetary values of the wider impacts

	Wider impact	Included in the value	Reference
WI1	Air quality: NH_3	Cost of morbidity and mortality arising from secondary PM formation. Recommended use for UK national evaluation. 2015 prices.	Defra (2015)
WI2	Air quality: NO_x	Cost of morbidity and mortality arising from secondary PM formation. Recommended use for UK national evaluation. 2015 prices.	Defra (2015)
WI3	Air quality: PM	Cost of morbidity and mortality from direct exposure and value of building soiling. Recommended use for UK national evaluation. 2015 prices.	Defra (2015)
WI4	Air quality: other: sulphur dioxide	Cost of morbidity and mortality from direct exposure, from secondary PM formation and value of building damage. Recommended use for UK national evaluation. 2015 prices.	Defra (2015)
WI9	Flood management	Estimated flood damage values are available in the SEPA Flood Risk Management Strategies.	SEPA (2015)
WI18	Human health	Impact on both life years and quality of life based on willingness to pay.	(Glover and Henderson 2010)

A1.1 Research gaps

The review revealed certain areas where the evidence about likely adverse impacts is not robust. Improving the evidence base in such cases can ensure that policies minimise these effects while maximising GHG benefits. WIs that can be either co-benefits or adverse impacts depending the way the MO is implemented also require further investigation to ensure that total benefits are maximised. However, research capacity in terms of modelling the WIs is not equally well developed for all MOs and WIs, as detailed in Section 3.2. Table 11 presents those MO–WI combinations in red where there is a highlighted research need but inadequate modelling capacity was found. This emphasizes the need for investment in further research and development of modelling capability. The four wider impacts most affected were soil quality, biodiversity, animal health and welfare and human health. Orange cells in the same table indicate those areas where the highlighted research need can be more readily answered by existing models. This mainly relates to three MOs: optimal soil pH, reduced livestock product consumption and afforestation.

The nature of greenhouse gas effect implies that GHG mitigation is not a spatial issue. However, most of the co-benefits and adverse effects are highly sensitive to the location of the land use or farm management change. To maximise the net benefits at regional or national level, spatially explicit integrative approaches are needed.

Furthermore, decision support tools which integrate the different environmental, economic and social aspects at a high level and offer standardised and more comprehensive appraisal could be useful tools for policy makers.

Table 11 Areas highlighted for further research

		WI1 Air quality: NH3	WI2 Air quality: NOx	WI3 Air quality: PM	WI4 Air quality: other	WI5 Water quality: N leaching	WI6 Water quality: P	WI7 Water quality: other	WI8 Soil quality	WI9 Flood mgmt, water use	WI10 Land cover and land use	WI11 Biodiversity	WI12 Animal health and welfare	WI13 Crop health	WI14 Household income	WI15 Consumer and producer surplus	WI16 Employment	WI17 Resource efficicency	WI18 Human health	WI19 Social impacts	WI20 Cultural impacts
MO1	On-farm renewables								[yellow]		[red]	[red]				[yellow]					
MO2	Precision farming												[red]				[yellow]			[red]	
MO3	Optimal soil pH									[yellow]		[red]									
MO4	Anaerobic digesters			[yellow]		[yellow]	[yellow]		[red]										[yellow]		
MO5	Agroforestry																				
MO6	More legumes					[yellow]															
MO7	Optimal mineral N use																				
MO8	Manure storage and application				[yellow]				[red]						[yellow]			[yellow]	[red]		
MO9	Livestock health							[yellow]				[red]							[red]		
MO10	Reduced livestock product consumption							[yellow]	[yellow]	[yellow]		[yellow]	[red]		[yellow]	[yellow]	[yellow]			[red]	[yellow]
MO11	Afforestation												[red]		[yellow]	[yellow]	[yellow]				[yellow]
MO12	Peatland restoration							[red]			[yellow]			[red]	[yellow]				[red]		[yellow]

[red]	No adequate models found to quantify negative effect with weak or moderate existing evidence
[yellow]	Models exist to quantify negative effect with weak or moderate existing evidence

4 Potential wider impacts of GHG mitigation in the waste sector

4.1 Employment benefits of diversion from landfill to recycling

4.1.1 Potential employment benefits in Scotland

The estimation of waste industry employment impacts hinges on the derivation of figures for the rate of employment per tonne of waste managed in different operations (e.g. collection, landfilling, incineration, etc.). This is based on the assumption that the rate of employment per tonne of waste managed for different management operations differs. The relative differences in treatment destinations can then be used to calculate the change in the number of FTEs across a range of scenarios. Hence, the key inputs required to derive employment impacts are:

1. The estimated mass flow of various waste materials in the modelled scenario;
2. The change in tonnages managed under different waste management operations; and
3. The employment rate i.e. number of FTEs per tonne of each type of waste managed under each operation.

Employment is then usually estimated in terms of number of FTE jobs per 10,000 tonnes of waste processed (also referred to as ‘employment intensity’). Employment intensity factors can be scaled in order to derive:

1. In the first instance, employment generated under a particular waste management scenario; and
2. More importantly, the net employment impact from a waste management policy proposal scenario compared to the counterfactual or baseline case.

The graphical overview of a basic employment impact model is provided in Figure 1. This example is taken from European Commission and involved modelling employment factors in relation to a range of waste management processes across a range of scenarios (Eunomia 2014).

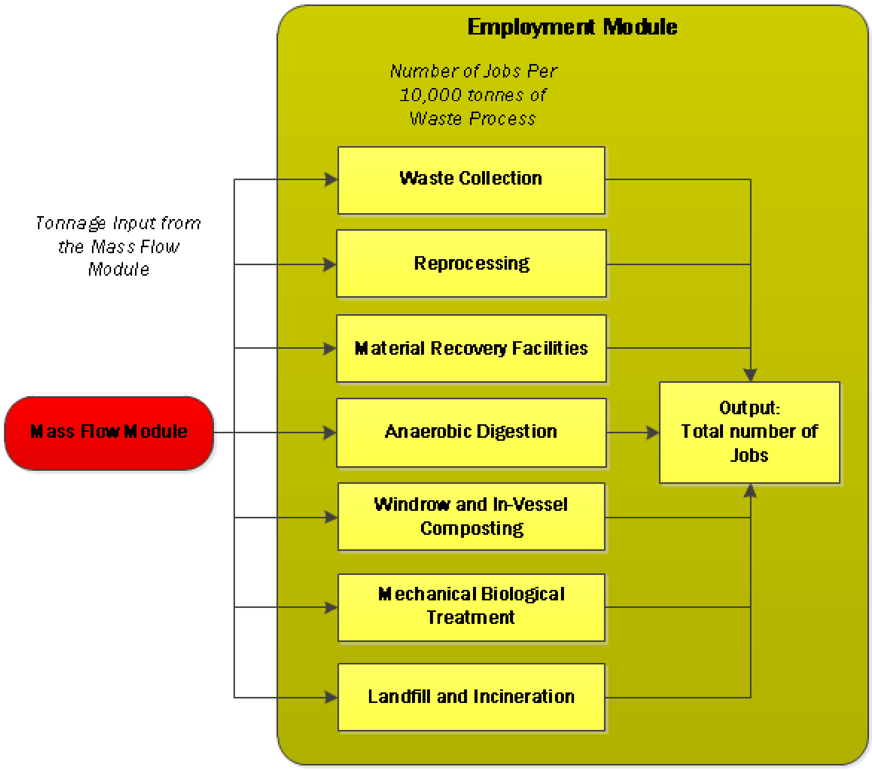

Figure 1 Example overview of employment modelling

4.1.2 Summary of findings of literature review

The estimate of employment benefits relies on the derivation of employment intensities, which in turn depends on waste mass flow and management data. A review of the available information for such data was carried out, with evidence presented by both waste management operation and material in Sections 4.1.2.1 and 4.1.2.2 respectively. The range of employment intensity estimates the literature reviewed is summarised in Table 12. Although a reasonable number of known information sources have been studied, the review is not exhaustive.

Table 12 Employment intensities from various data sources (full time equivalents (FTEs) per 10,000 tonnes per annum)

Study	Landfill	Incinerator	MBT	Composting	Windrow	In-vessel	AD	Residual Waste Collection	Recycling Collection	Recycling Collection/ Reprocessing
SWAP, 1997 (UK)										3-67
Murray, 1999 (UK)	≈ 1	≈1						6	21–40	2
Gray *et al.* 2004 (UK)									5 (biowaste)	4-19
Seldman, 2006 (USA)	1	1		4						25
Urban Mines and Walker Resource Management, 2012 (UK)			5		2		2			
Eunomia, 2014 (EU)					4		2			
TBU and Eunomia, 2003			2 - 3							
University of Glamorgan, 2007 (AU)			5							
Greenpeace, 2009		5								
Cottica & Kaulard, 1995	≈ 1	2-4								
European Commission, 2006										12
Friends of the Earth, 2010									32	49
Selected figure for modelling	1	1	4	4	4	2	2	6	Material specific data for recycling and reprocessing is in Section4.1.2.2)	

Notes: Figures are rounded to nearest integer. It is important to note that whilst Seldman's study was published in 2006, the data was collected in 1997.

4.1.2.1 Employment by waste management operation

Research indicated that the level of conformity in employment estimates varies between the different waste management operations. The literature review for landfill for example, which is an established disposal route, found far greater conformity in results compared to reprocessing technologies. Variation in the levels of mechanisation and technology between reprocessing facilities may contribute to the large range in employment intensities presented in different studies.

4.1.2.1.1 Landfill

Despite the date of research and lack of methodological transparency, the conformity of the results from the Seldman (2006), Murray (1999) and Cottica & Kaurlard (1995) studies imply that 1 is an acceptable figure to use for modelling. Being typically large scale (high throughput) facilities with respectively low process technology (landfill) these figures appear reasonable compared to the results for other technologies.

4.1.2.1.2 Incineration

The most recent study by Greenpeace (2009) about incineration in Spain gives an estimate of 4.8 jobs per 10,000 tonne per annum (tpa) based on 10 incinerators operational at the time in Spain. However, the report does note that the figure varies significantly between plants, giving the example of the 280,000 tpa Zagalgabri facility operated by just eleven people (equivalent to 0.4 FTEs per 10,000). A lower employment intensity of 1FTE/10,000t is found in both the Murray (1999) and Seldman (2006) studies, with the Cottica & Kaulard study (1995) presenting a range from 1.9-3.7 FTE/10,000t.

Based on the literature findings, and given that incineration in most instances is a large scale highly mechanised process, a figure of 1 FTE/10,000t is considered reasonable.

4.1.2.1.3 Mechanical biological treatment

A detailed report on MBT (TBU and Eunomia 2003) gives personnel requirements as reproduced in Table 13. This suggests that a basic minimum number of staff are required for an MBT facility. The data indicates that at smallest viable scale for such a facility (40,000 tpa as indicated in the source reference), staff numbers may total perhaps 12 FTEs, or 3 employees per 10,000 tpa of capacity.

Table 13 Personnel requirements of a mechanized MBT with fermentation (source: TBU and Eunomia, 2003)

Function	Responsibility	Number of Staff
Operating manager	Whole plant	1
Deputy operating manager	Fermentation	1
Electrician, electronics engineer	EMSR (Electrical, measurement, control and regulation technology)	1-2
Fitter	Maintenance, repair	1
Mobile equipment operator	Wheel loader, grab excavator, container vehicles	3-4
Cleaning staff	Daily cleaning and cleaning of the grounds, externally if necessary	2-3
Laboratory staff	Process control, material analysis	Proportional
Replacement	Estimation: ~ 25-30%	Proportional
Administration		Proportional
Weighbridge, workshop		Proportional
Data administration, marketing		Proportional

A comprehensive survey of the UK organics industry by WRAP elicited data for 10 MBT plants (Urban Mines and Walker Resource Management, 2012). The data was subsequently upscaled to account for plants that did not partake in the survey. Whilst WRAP's figures for AD and composting are calculated from site's annual material input, the employment figure for MBT was based on the plant's annual capacity. Data given in the report's Appendix 5, reveals that the 10 MBT sites successfully surveyed average 74,600 tpa of material input for an average 83,000 tpa of total annual capacity, and with an average 35.6 employees per facility. As such, we can derive an employment intensity of 4.8FTE per 10,000 tpa of throughput.

One further reference is available for a 100,000 tpa facility in Austria incorporating mechanical (and manual) sorting, percolation and AD, biodrying, mechanical material separation (heavy/light fraction separation for SRF production), exhaust gas treatment and onsite disposal to landfill. The report states that "ZAK Ringsheim has 50 employees in total, including many administrative staff". A more simple MBT facility (without the digestion element), and where landfill is considered as a separate activity may be expected therefore to employ less than this 5 FTE per 10,000 tpa figure. Based on these comparisons, a figure of 4 FTE per 10,000 tpa is recommended for modelling.

4.1.2.1.4 *Windrow and in-vessel composting*

WRAP's study surveyed 199 composting sites across the UK (Urban Mines and Walker Resource Management, 2012). Whilst these included windrow, in-vessel and also aerated pile composting facilities, aerated pile accounted for <1% of the surveyed input and thus did not significantly show in the results.

Note that the report did not go into details of individual sites. Eunomia's research demonstrated an inverse relationship between site size and employment intensity for windrow composting sites (as may be expected), albeit with very few data points (Eunomia, 2014). However, this does not fully explain the differences between Eunomia's and WRAP's results: the average input per site for WRAPs study was 19,186 tpa compared to an average of 18,000 for this study.

The lack of available data points give very little upon which to base our assumptions, but the Eunomia (2014) study suggests a figure of 4 FTEs per 10,000 tpa may be reasonable for windrow compositing. The lower figure of 2 FTEs per 10,000 tpa is selected for in-vessel composting in order both to be conservative and to match the figure for AD.

4.1.2.1.5 *Anaerobiic Digestion*

WRAP's study surveyed 19 out of the total 48 AD sites in the UK, indicating an average of 2 FTEs per 10,000 tpa of capacity. Neither WRAP's (Urban Mines and Walker Resource Management, 2012) nor Eunomia's micro study (2014) focused specifically on AD sites processing food waste. Both studies, however, discerned a similar mean employment intensity. The data is not sufficient to show any trends for employment intensity varying with facility throughput. The conformity of WRAP's value with Eunomia's supports its use in employment modelling.

4.1.2.1.6 Waste collection and reprocessing

Table 14 illustrates the results from a study for DEMOS on waste and recycling collection systems (Murray, 1999). They clearly demonstrate higher employment intensity for recycling than residual waste collection. The values for recycling in particular are inclined to change, however, as recycling systems and rates have changed dramatically since the time of publication.

Table 14 Employment intensity for waste collection (FTEs per 10,000 tpa) (source: Murray,1999)

	Number of Staff
Recycling collection	≈ 21 – 40
Residual waste collection	≈ 6

Where recycling is concerned, data in the literature often conflates employment in waste collection with that in sorting and in reprocessing. There is some sense in this approach, as studies often attempt to demonstrate in a straightforward manner the additional employment associated with additional recycling, and thus the factors used include collection, sorting and reprocessing combined. This also minimises issues where employment moves between collection and sorting operations depending on the degree of separation during the collection operation. However, where studies focus on the employment created by additional recycling, they tend to miss the potential loss of employment associated with residual waste collection.

4.1.2.2 Employment by Material

Data on employment for reprocessing further suggests that employment intensity varies considerably depending on the material which is being reprocessed. Table 15 shows employment intensity by material reprocessed, based on data from SWAP (1997), ranging from 3 FTE/ 10,000 tpa for glass reprocessing to 67 FTE/ 10,000 tpa for plastics reprocessing. However, note that this data is almost 2 decades old.

Table 15 Employment for reprocessing by material (SWAP, 1997)

Material	Employees/10,000 t (includes admin and reprocessors)
Paper and Card	19
Glass	3
Steel	5
Aluminium	11
Plastic	67

The Seldman (2006) study of the US reprocessing industry also found a high employment intensity for plastics reprocessing in comparison to other materials. The study found that 93 FTE were employed per 10,000 t of plastic reprocessed and paper was the least employment intensive material to reprocess (18 FTE/ 10,000t).

A further study undertaken by LEPU in 2004 refers to job gains by quantity of material reprocessed. But that 'job gains' is not the same as employment intensities and therefore are not directly comparable with the previous source. In this case, the data includes employment related to collection and sorting operations in addition to that associated with reprocessing.

A 2006 report by the European Commission includes an assessment of the impact of the packaging directive obligations on the direct and first round indirect employment rate in the packaging recovery and recycling industry. This gives a figure of 42,000 FTEs which may be associated with the stated 36 million tonnes recovered (in 2002) indicating around 12 FTEs per 10,000 tpa (European Commission, 2006). Again, however, this might not be a directly comparable figure as the other sources do not seem to include the first round indirect employment – i.e. employment up and down-stream resulting from new direct employment in the recycling sector.

A more recent study by Friends of the Earth (2010) reviews employment intensities from a number of sources. It identifies that employment in different studies is taken to include some of all of the following activities associated with recycling:

- Collectors;
- Brokers (purchasing recyclable commodities for resale);

- Processors (businesses that bale, crush, pelletise, compost, demanufacture or otherwise change the form of the recyclable material for sale);
- End users / recycling manufacturers (businesses that use recyclable materials as feedstock in the production of a new product);
- Reusers or remanufactures (businesses that remanufacture or reuse recyclable material such as furniture, white goods, computers and electronic appliances, wood, as well as retailers that sell used merchandise);
- Recycling equipment manufacturers.

Table 16 reproduces the sources reviewed and assumptions taken by Friends of the Earth (2010) for the key recyclable materials considered in that study, and adds additional materials of interest. This study also applied a multiplier of 1.5 for first round indirect employment, which was increased to 1.75 for the inclusion of induced employment from expenditure of the additionally employed individuals.

Table 16 Employment intensity for recycling by material (FTEs/10,000 tpa)

Material	Gray *et al.* 2004	Cascadia (2009) citing Seldman (2006)	Friends of the Earth (2010) Value for 2020	Eunomia 2014
Glass	7.5	26	7.5	7.5
Paper	35	18	18	18
Plastic	156	93	93	93
Iron & Steel	54	-	54	54
Aluminium	110	-	110	110
Wood	7.5	-	7.5	7.5
Textiles	50	85	50	50
WEEE	400	(computer reuse) 296	-	400
Furniture	136	-	-	136
Biowaste	5 collection + 8 processing	4	4	5 collection
MRFs	-	10	-	-
Average all recycling	62	50	49	-

4.1.3 Issues with the Quality of Data

Given the findings of the above review, several key shortcomings associated with the data come to light. The OECD has previously recognised these intrinsic difficulties in the analysis and interpretation of employment data in the waste management industry (OECD 1996). The key issues highlighted in the evidence reviewed are outlined below:

4.1.3.1 Lack of recent data

Many of the studies reviewed were conducted over a decade ago. The literature search suggests that a limited number of primary research studies have been conducted, and these are repeatedly cited in more recent studies. This poses a particular problem for waste industry data due to the scale of development that has taken place since the 1990s. For example, in the case of sorting facilities (or material recycling facilities – MRFs) where facilities have grown in size (perhaps relating to increasing rates of recycling over time) economies of scale are likely to have been experienced, reducing the employment intensity. Reprocessing technology and changes in the design of products that end up in recycling schemes are also likely to have had significant effects on MRF employment over time.

4.1.3.2 Lack of methodological transparency

This was the case with many of the studies reviewed. A widely cited report by Gray *et al.* (2004), for example, fails to properly reference or provide additional information on its sources of information. One reference is simply labelled “EU report”. A similar instance can be seen in a study by Murray (1999), where no reference is given to the methodology behind the employment figures. Without access to the methodology behind these figures, it is difficult to understand what they relate to and, in turn, their practical utility.

4.1.3.3 Employment metric

A number of reports refer to number of employees as opposed to FTEs. In these cases, number of employees may not be directly comparable to number of FTEs. There is also inconsistency and difficulty in identifying the operations that qualify within the scope of employees being estimated. For example, a facility will have operational staff, but there are also likely to be office staff involved in the operation of the facility, some of whom may be responsible for a number of facilities. It is difficult to identify if their time has been included and if time has been apportioned between facilities.

4.1.3.4 Inclusion of indirect/ induced/ displacement employment

Certain studies, particularly related to recycling collection and processing, sometimes include indirect employment (i.e. employment up and down-stream resulting from new direct employment in the recycling sector) and induced employment (i.e. that associated with expenditure of the directly employed individuals) within the estimation of employment factors. Others (e.g. Eunomia 2014) takes account of displacement factors within the estimation of employment intensity. This is an important consideration, since a shift to a new waste management system will inevitably displace some employment in other operations, either via direct labour, or due to shifting purchasing power away from certain technologies (indirect unemployment). Hence, net employment creation will always be less than gross estimates, and may even be zero or negative.

4.1.3.5 Distribution of impacts

The literature reviewed provides limited information on the distribution of the various estimated employment benefits arising from shifting waste management operations. This is true firstly in terms of geographical distribution. This is related to both waste operation type (for example, closed loop recycling plants tend to be located near manufacturing sites and supply chains, and hence increased recycling by this method will not have evenly distributed employment benefits across the UK) and also to regional variations in the labour market.

Further, the literature also tends to skip over the proportion of employment benefits that can be allocated across the range of labour skill levels. A literature review on the nature of employment created in the circular economy (including shifting waste management practices) was carried out by the Green Alliance (2015) and is summarised in Table 17. This research went on to estimate that net job creation in circular economy activity to 2030 at the current growth rate in Scotland would be 0.07% of the labour force. This is not comparable to earlier estimates as it estimates employment generated across several circular economy activities rather than simply landfill diversion to recycling.

Table 17 Literature on the nature of employment creation in circular economy activities (source: Green Alliance, 2015)

Sector	Study	Coverage	Skill level of jobs created
Recycling	EEA (2011)	EU	Low skilled work in particular, but also medium and high skilled jobs, ranging from collection, materials handling and processing to manufacturing products.
	ILO (2011)	Germany	16% low skilled, 47% skilled, 11% technical, 25% university.
Waste collection	ECOTEC (2002)	EU	Labour required for waste collection and transport, at relatively low wage rates.
Remanufacturing	APPSRG (2014)	UK	Skilled, with substantial training needs
	Beck (2011)	USA	Relatively high skill and training requirements.
Waste Management	SITA (2012)	UK	A range of jobs, but particularly significant numbers of mid-level (supervisors/ operators) and low level (manual) occupations.

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Appendix A1. Qualitative assessment of the wider impacts of ALULUCF GHG mitigation options

A1.1 Developing on-farm renewable energy sources (MO1)

This MO reduces GHG emissions by increasing small scale renewable energy generation on farms, including wind and solar energy and biomass boilers (AD is discussed in Section A1.4).

Table 18 Wider impacts of MO1

Mitigation option:		**Developing on-farm renewable energy sources (MO1)**		
Impact		**Direction/ magnitude**	**Notes**	**References**
WI1	Air quality: NH_3	0	Across all farm scale renewable technologies this is unlikely to be an important impact, however, biomass burning can increase NH_3 emissions.	Saidur *et al.* 2011
WI2	Air quality: NO_x	+	A positive effect as combustion processes are replaced by renewable energy sources (apart from biomass combustion based renewables).	RoTAP 2012
WI3	Air quality: PM	+	A positive effect in reducing particulate emissions as combustion processes are replaced by renewable energy sources (apart from biomass combustion based renewables).	RoTAP 2012
WI4	Air quality: other	+	A reduction in NO_x reduces the secondary pollutant formation of ground level ozone.	Gonzalez-de-Soto *et al.* 2016
WI5	Water quality: Nitrogen leaching	0	No evidence found, unlikely to be a significant impact.	
WI6	Water quality: Phosphorous	0	No evidence found, unlikely to be a significant impact.	
WI7	Water quality: other	0	For renewables, such as hydro schemes, legislation such as Water Framework Directive and River Basin Management Plans, provide appropriate guidance and help to limit the impact on the water environment.	Copestake 2006
WI8	Soil quality	+/-	More research is required to determine the impact of solar developments on plant-soil carbon recycling. The effect of wind farms varies depending on terrestrial setting of schemes.	Armstrong *et al.* 2014 Nayak *et al.* 2008, Nayak *et al.* 2010, Smith *et al.* 2011
WI9	Flood management, water	0	No evidence found, unlikely to be a significant impact.	

Mitigation option:		Developing on-farm renewable energy sources (MO1)		
Impact		**Direction/ magnitude**	**Notes**	**References**
	use			
WI10	Land cover and land use	-	Renewable schemes tend to take up larger areas of land for the amount of power produced compared to conventional energy generation and fossil fuels.	Bergmann *et al.* 2006
WI11	Biodiversity	0/-	No direct on-farm biodiversity effect is expected. Indirect positive effect though reduced air pollution is expected. Conflicts are likely to increase between energy developments and biodiversity as the number of schemes increase, for example regarding freshwater pearl mussels.	RoTAP 2012 Young *et al.* 2010 Addy *et al.* 2012
WI12	Animal health and welfare	0	No evidence found, unlikely to be a significant impact.	
WI13	Crop health	0	No evidence found, unlikely to be a significant impact.	
WI14	Household income	+	Farmers' income: boost to household income through incentive payments from government environmental programmes such as Feed in Tariffs. Recent government changes to incentive schemes could impact this. Income distribution: no significant impact is expected, though the distribution of the positive impact might be uneven as less prosperous farms might not be able to find the capital for the investment.	Cherrington *et al.* 2013 Phimister and Roberts 2012
WI15	Consumer and producer surplus	+/-	Varied results depending on siting and type of development. Increase to electricity prices reduces consumer utility.	Bergmann *et al.* 2006
WI16	Employment	+	Diversification of farm business and increase in employment opportunities and job retention. Impacts can depend on use of additional incomes.	Bergmann *et al.* 2008, Phimister and Roberts 2011
WI17	Resource efficiency	+	Renewables reduce the need for non-renewable energy generation.	
WI18	Human health	+/-	Positive indirect effect through reduced air pollution. Potential negative effect from the noise of small and micros scale wind turbines.	Haines *et al.* 2006 Taylor *et al.* 2013
WI19	Social impacts	+	Community ownership of renewables (relevant to a number of on-farm projects) leads to a more positive outlook and more locally involved approach to developments than large	Warren & McFadyen 2010

Mitigation option:		Developing on-farm renewable energy sources (MO1)		
Impact		Direction/ magnitude	Notes	References
			scale developments. Renewables can lead to the sustainable development of communities across Scotland.	
WI20	Cultural impacts	0	On-farm renewables, due to their small scale, are unlikely to have a considerable impact on landscape or cultural heritage.	

A1.2 Increased uptake of precision farming techniques (MO2)

Precision farming includes management practices and a wide range of technologies which enable the farmer to obtain and analyse more precise information on the soil, crop and animal qualities in order to respond with management specific to the in-field variation or to the individual livestock. Most importantly to GHG emissions these practices can improve how nitrogen and livestock feed resources are used on farm, reducing N_2O emissions, energy use by machinery, and/or the GHG emission intensity of crop and livestock products (Eory *et al.* 2015).

Table 19 Wider impacts of MO2

Mitigation option:		Increased uptake of precision farming techniques (MO2)		
Impact		Direction/ magnitude	Notes	References
WI1	Air quality: NH_3	+	Some potential reduction is associated with improved spatial applications of fertiliser nitrogen. Optimizing the method of spreading can also decrease NH_3 emissions (see Section A1.8).	Novak and Fiorelli 2010
WI2	Air quality: NO_x	+	Increased fuel efficiency in machinery can reduce NO_x emissions.	Gonzalez-de-Soto *et al.* 2016
WI3	Air quality: PM	+	See NO_x above.	Gonzalez-de-Soto *et al.* 2016
WI4	Air quality: other	+	A reduction in NO_x reduces the secondary pollutant formation of ground level ozone.	Sutton ed. 2011
WI5	Water quality: Nitrogen leaching	+	Potential improvements associated with reduced nitrate losses if the use of Nitrogen fertilisers is more precisely targeted to crop demand.	Clough *et al.* 2004
WI6	Water quality: Phosphorous	+	Potential improvements associated with reduced phosphate losses if the use of phosphate fertilisers is more	Rains *et al.* 2001

Mitigation option: Impact		Increased uptake of precision farming techniques (MO2) Direction/ magnitude	Notes	References
			precisely targeted to crop demand.	
WI7	Water quality: other	+	Precision pesticide applications would be likely to reduce the overall loss of pesticides to water.	Bajwa *et al.* 2015
WI8	Soil quality	+	Information on soil wetness and precision management of soil for example through precision fertiliser application would allow the development of spatially explicit management operations which would reduce machinery traffic and thereby contribute to potential improvements in soil quality.	Bajwa *et al.* 2015, Sylvester-Bradley *et al.* 1999
WI9	Flood management, water use	+	Can potentially reduce water resources abstraction from wells/rivers if irrigated crops such as potatoes, salad crops, root vegetables and soft fruit are irrigated using precision irrigation systems in conjunction with soil moisture monitoring systems.	http://www.ukia.org/pdfs/switching%20technologies.pdf
WI10	Land cover and land use	0	No evidence found, unlikely to be a significant impact.	
WI11	Biodiversity	+	Precision farming can reduce pesticide use and thus improve on-farm biodiversity.	Timmermann et al. 2003
WI12	Animal health and welfare	+/-	Provides opportunities for better health and nutritional monitoring, but may impact on welfare, e.g. robotically milked cows unlikely to be grazed on pastures.	Wathes *et al.* 2008
WI13	Crop health	+	Provides better opportunity to match fungicide products to disease risk.	Poole and Arnaudin 2014
WI14	Household income	+	Farmers' income: various opinions are represented in the literature. There is an argument that improved technology will allow farmers to generate increased income and hence become more profitable, though on smaller farms the costs can easily outweigh the financial benefits. Income distribution: no significant impact is expected, though the distribution of the positive impact might be uneven as less prosperous farms might not be able to find the capital for the investment.	Rosch and Dusseldorp 2007, MacLeod *et al.* 2015
WI15	Consumer and producer surplus	+	No evidence found. Higher efficiency can increased the producer surplus for the farmer and, if large scale efficiency improvements reduce the prices of agricultural products that can increase consumer surplus.	

Mitigation option: Impact		Increased uptake of precision farming techniques (MO2)		
		Direction/ magnitude	Notes	References
WI16	Employment	-	Potential reduction in rural employment given the likelihood that new technologies would replace existing employees (e.g. robotic milking).	Sassenrath *et al.* 2008
WI17	Resource efficiency	+	Improved resource use efficiency associated with precision management is likely.	Rosch & Dusseldorp 2007
WI18	Human health	+	Potential benefits resulting from reduced nutrient loss to air and water.	Sutton *et al.* 2011
WI19	Social impacts	+/-	Reduced employment opportunities and the tendency for precision management technology to be associated with higher income employers could potentially reduce social cohesion. If PF machinery is pooled the increased importance of co-ops might improve cohesion.	Sassenrath *et al.* 2008
WI20	Cultural impacts	0	No evidence found, unlikely to be a significant impact.	

A1.3 Achieving and maintaining optimal soil pH level (MO3)

For optimal soil chemistry, nutrient availability and plant growth it is recommended that the pH of arable soils is maintained at 6 or above and that for grassland soils at 5.8 or above (SRUC 2015). Sub-optimal liming on acidic soils leads to less efficient use of plant nutrients and can also result in a larger proportion of nitrogen applied being released as N_2O (Baggs *et al.* 2010).

Table 20 Wider impacts of MO3

Mitigation option: Impact		Achieving and maintaining optimal soil pH level (MO3)		
		Direction/ magnitude	Notes	References
WI1	Air quality: NH_3	+/-	Increasing soil pH is likely to increase nitrogen use efficiency, but higher pH can also lead to increases in NH_3 volatilisation.	Goulding 2016
WI2	Air quality: NO_x	0	No evidence found, unlikely to be a significant impact.	
WI3	Air quality: PM	0	No evidence found, unlikely to be a significant impact.	
WI4	Air quality: other	0	No evidence found, unlikely to be a significant impact.	
WI5	Water quality: Nitrogen leaching	+	Increasing soil pH is likely to increase nitrogen use efficiency, which would therefore lead to lower nitrogen leaching.	Goulding 2016
WI6	Water quality:	+	Increasing soil pH generally reduces	Goulding

Mitigation option: Impact		Achieving and maintaining optimal soil pH level (MO3) Direction/ magnitude	Notes	References
	Phosphorous		the availability of phosphate in soils and therefore reduces the leaching risk	2016
WI7	Water quality: other	+	Possible reduced loss of heavy metals.	Goulding 2016
WI8	Soil quality	+	Soils with higher pH generally have improved fertility, which is an indicator of good soil quality.	Goulding 2016
WI9	Flood management, water use	+/-	May positively or negatively affect evaporation and runoff generation processes at field/farm scales due to changes in soil structure which could affect water holding capacity.	Goulding 2016
WI10	Land cover and land use	0	No evidence found, unlikely to be a significant impact.	
WI11	Biodiversity	+/-	The diversity of plant communities is influenced by soil pH, however net effects of pH changes are difficult to predict.	Olsson *et al.* 2009
WI12	Animal health and welfare	+	Reduced influence of liver fluke.	Mccann *et al.* 2010
WI13	Crop health	+	Improved crop growth associated with better crop health.	Janvier *et al.* 2007
WI14	Household income	+	No evidence found, a small positive impact can be expected from increased productivity.	
WI15	Consumer and producer surplus	+	No evidence found, the potentially increased productivity can increase the producer surplus.	
WI16	Employment	0	No evidence found, unlikely to be a significant impact.	
WI17	Resource efficiency	0	No evidence found, unlikely to be a significant impact.	
WI18	Human health	+	Reduced availability of heavy metals in soils might lead to lower exposure via human consumption.	Podar and Ramsey 2005, Smith 1994
WI19	Social impacts	0	No evidence found, unlikely to be a significant impact.	
WI20	Cultural impacts	0	No evidence found, unlikely to be a significant impact.	

A1.4 Anaerobic Digestion for manure processing (MO4)

AD of manure can reduce the CH_4 emission from the manure storage and can provide alternative energy sources thus providing further, indirect, GHG savings. In this assessment the focus was on small community scale (around 750KW – 1 MW) AD digesting manure and additional biomass. The most critical factors that impact the environmental sustainability of AD plants are the feedstock type, feedstock source (the proportion of manure, the source of additional biomass, e.g. food waste or purpose-grown crops), digestate storage and how the digestate is spread to land (Whiting & Azapagic, 2014) which can vary greatly from plant to plant. Also it is important to consider what the existing land use is and whether there will be a significant land use change, or if existing waste products are being used, providing an additional benefit to their conventional use/storage.

Table 21 Wider impacts of MO4

Mitigation option:		**Anaerobic digesters for manure processing (MO4)**		
Impact		**Direction/ magnitude**	**Notes**	**References**
WI1	Air quality: NH_3	-/0	AD plants concentrate organic wastes, concentrating distributed sources of NH_3 emissions. NH_3 emissions are dependent on site management practices concerning the handling, storage and treatment of organic wastes and the digestate. The storage of solid digestate and the aerobic treatment of liquid effluents are the greatest sources of NH_3 emissions. NH_3 emissions can be higher from digestate than from slurry if the storage tank is uncovered. Covered digestate storage can capture up to 80% of CH_4 and NH_3 from AD. A digestate cover that collects biogas provides additional energy production option. At spreading there are a number of competing factors compared with untreated slurry – greater total ammoniacal nitrogen and higher pH encouraging loss but lower dry matter which encourages more rapid infiltration and reduces loss. The literature is mixed, however, low NH_3 emission spreading techniques (see Section A1.8) can reduce NH_3 loss by 60%.	Bell *et al.* 2016, Moeller & Stinner 2009 Cumby *et al.* 2005 Reis ed. 2015, Whiting and Azapagic 2014 Amon *et al.* 2006, Battini *et al.* 2014, Chantigny *et al.* 2009, Pain *et al.* 1990
WI2	Air quality: NO_x	-	Combustion of produced biogas in engine can increase NO_x emissions, however this can be limited by improvements to biogas combustion technologies.	Battini *et al.* 2014
WI3	Air quality: PM	-	Emissions of NH_3 can lead to ammonium nitrate PM formation. AD, as a local combustion site, can shift the PM emissions from where the conventional power stations are.	Rotap 2012

Mitigation option: Impact		Anaerobic digesters for manure processing (MO4) Direction/ magnitude	Notes	References
WI4	Air quality: other	0	No evidence found, unlikely to be a significant impact.	
WI5	Water quality: Nitrogen leaching	+/-	The literature is inconclusive, some experiments finding lower, others higher nitrogen leaching from digestate than from raw slurry. Best management practices can help mitigating negative effects.	Nkoa 2014
WI6	Water quality: Phosphorous	-	No evidence found, higher concentration of phosphorous in digestate than in raw slurry might pose risk of increased runoff.	Nkoa 2014
WI7	Water quality: other	0	No evidence found, unlikely to be a significant impact.	
WI8	Soil quality	+/-	Grassland yields were found to be higher with digestate than with slurry, potentially as a result of enhanced plant available nutrients. Long term accumulation of micronutrients (e.g. copper, zinc) can occur, impeding soil quality.	Walsh *et al.* 2012 Nkoa 2014
WI9	Flood management, water use	0	No evidence found, unlikely to be a significant impact.	
WI10	Land cover and land use	0	Varying results depending on previous land use and production systems used. Land use change away from conventional food crops is sometimes thought to be a concern, approximately 0.5% of UK arable cropping land is used for growing crops for AD and the current risk for intensive production of a single crop as monoculture is seen as low.	Börjesson & Tufvesson 2011 Röder 2016
WI11	Biodiversity	0	No evidence found, unlikely to be a significant direct impact on on-farm biodiversity.	
WI12	Animal health and welfare	0	No evidence found, unlikely to be a significant impact.	
WI13	Crop health	0	No evidence found, unlikely to be a significant impact.	
WI14	Household income	+	Farmers' income: costs of installing plant can be expensive. Benefits for developers is available through incentive payments s, however changes to incentive schemes could impact this. Also using existing waste streams to meet on site energy demands can significantly lower bills. Income distribution: no significant impact is expected, though the distribution of the positive impact might be uneven as less prosperous farms	Röder 2016

Mitigation option: Impact		Anaerobic digesters for manure processing (MO4) Direction/ magnitude	Notes	References
			might not be able to find the capital for the investment.	
WI15	Consumer and producer surplus	+	No evidence found, increased income could mean higher producer surplus.	
WI16	Employment	+	Across the UK it is estimated that the number of jobs in biomass combustion and AD would be 35,000 – 50,000 by 2020. Employment potential is predicted to be higher than other renewable technologies due to additional elements of feedstock production, supply and plant operation.	McDermott 2012
WI17	Resource efficiency	++	AD recycles energy embedded in agricultural and other waste sources.	
WI18	Human health	+/-	Increasing the amount of renewables can help mitigate the negative impacts of climate change on human health and air pollution. At the same time the more dispersed combustion can require additional effort in reducing pollution and there is an indirect negative effect from increased NH_3 emissions.	Haines *et al.* 2006
WI19	Social impacts	+	Community schemes could bring a sense of public engagement if done effectively.	Walker *et al.* 2010
WI20	Cultural impacts	0	No evidence found, unlikely to be a significant impact.	

A1.5 Agroforestry (MO5)

Agroforestry systems are multifunctional systems of woody vegetation (trees or shrubs) either combined with crops (silvoarable) or established on grazed pasture (silvopastoral). It also includes the use of trees and hedgerows as buffer zones. The trees and shrubs can be utilised for timber, fuel or fruit. The main GHG effect of agroforestry is the carbon sequestration in the vegetation and in the soil (Eory *et al.* 2015).

Table 22 Wider impacts of MO5

Mitigation option: Impact		Agroforestry (MO5) Direction/ magnitude	Notes	References
WI1	Air quality: NH_3	+	Trees are known to remove NH_3 from the atmosphere downwind of sources e.g. intensive livestock production.	Bealey *et al.* 2014
WI2	Air quality: NO_x	+	Reduction of NO_x emissions from fertiliser production and from soil, as a result of reduced use of nitrogen fertiliser per unit area.	Pacyna *et al.* 1991, Skiba *et al.* 1997
WI3	Air quality: PM	+	There is evidence for reduction of particulates and odour from shelterbelts.	Tyndall & Colletti 2007
WI4	Air quality: other	0	No evidence found, unlikely to be a significant impact.	
WI5	Water quality: Nitrogen leaching	+	Extended root net of multiple species with different root architecture can reduce losses.	Bergeron *et al.* 2011
WI6	Water quality: Phosphorous	+	Potential reduction in run off as trees act as landscape level buffers.	Jose 2009
WI7	Water quality: other	+	Reduced use of agrochemicals as a result of smaller area of arable or grassland per unit area. Also increased presence of natural enemies of pests due to increased agrobiodiversity can lead to reduced pesticide use.	Stamps and Linit 1997
WI8	Soil quality	+	The literature suggests that agroforestry stores more carbon than agricultural systems but there is relatively little evidence in temperate systems. Possibly more benefit to soil carbon from trees planted into arable systems than trees planted in grassland. Additionally, soil erosion is reduced.	Upson & Burgess, 2013, Beckert *et al.* 2016
WI9	Flood management, water use	+	Potential improvement due to buffer strip effect.	
WI10	Land cover and land use	+	Soil protection is likely to increase although very much depend on species combinations and management.	Mead 1995
WI11	Biodiversity	+	Increased species diversity in cropping can increase biodiversity.	McAdam *et al.* 2007
WI12	Animal health and welfare	+	Can provide shelter for animals – this can be shade in summer but also reduction of windchill in winter.	Karki & Goodman 2009
WI13	Crop health	+	Increased biodiversity and tree cover increases the presence of natural enemies to pests. This benefit can be enhanced by proper design.	Dix *et al.* 1995
WI14	Household income	0	No evidence found, unlikely to be a significant impact.	

Mitigation option:		Agroforestry (MO5)		
Impact		Direction/ magnitude	Notes	References
WI15	Consumer and producer surplus	0	No evidence found, unlikely to be a significant impact.	
WI16	Employment	0	No evidence found, unlikely to be a significant impact.	
WI17	Resource efficiency	0	No evidence found, unlikely to be a significant impact.	
WI18	Human health	+	The air and water quality improvements would have an indirect positive effect on human health, but no specific literature is found on this.	
WI19	Social impacts	0	No evidence found, unlikely to be a significant impact.	
WI20	Cultural impacts	+	Landscape diversity, provision of recreation and possible use of native or rare trees, including production of fruit and nuts for local consumption.	

A1.6 Incorporating more legumes in grass mixes and crop rotations (MO6)

Legumes have symbiotic relationships with bacteria which allow them to fix atmospheric nitrogen and use this in place of nitrogen provided by synthetic fertilisers. They are also able to supply nitrogen to crops they are mixed with (e.g. clover-grass mixtures) or to a certain extent to subsequent crops in a rotation (e.g. peas in one year and cereals in the next).

Table 23 Wider impacts of MO6

Mitigation option:		Incorporating legumes in grass mixes and crop rotations (MO6)		
Impact		Direction/ magnitude	Notes	References
WI1	Air quality: NH_3	+	NH_3 emissions will be reduced due to the reduction in nitrogen fertiliser applications. However, NH_3 emissions from the crop itself are likely to be higher than the baseline due to the residues of the legumes containing more nitrogen. The overall balance is likely to be positive.	Nett *et al.* 2015, Bath *et al.* 2006, Larsson *et al.* 1998, Mannheim *et al.* 1997
WI2	Air quality: NO_x	+	Reduction of NO_x emissions from fertiliser production and from soil, as a result of reduced nitrogen fertiliser applications.	Jensen and Hauggaard-Nielsen 2003
WI3	Air quality: PM	+	Indirect benefits resulting from the reduced nitrogen fertiliser production process. As the NH_3 emissions are likely to be reduced, there will be a reduction in the secondary PM formation.	Sutton ed. 2011

Mitigation option: Impact		Incorporating legumes in grass mixes and crop rotations (MO6) Direction/ magnitude	Notes	References
WI4	Air quality: other	0	No evidence found, unlikely to be a significant impact.	
WI5	Water quality: Nitrogen leaching	-	Increased risk of leaching during the post-harvest period from the biologically fixed nitrogen and crop residues compared to crops which receive fertilisers. This can be mitigated by having winter coverage of crops.	Jensen & Hauggaard-Nielsen 2003, Hauggaard-Nielsen *et al.* 2003, Engström & Lindén 2012
WI6	Water quality: Phosphorous	0	No evidence found, unlikely to be a significant impact.	
WI7	Water quality: other	0	No evidence found, unlikely to be a significant impact.	
WI8	Soil quality	+	Legumes improve soil fertility. Some legumes are deep rooting, and therefore can extract nutrients from deeper layers of the soil.	Jensen & Hauggaard-Nielsen (2003)
WI9	Flood management, water use	0	Unlikely to have a significant effect as long as leafy growth and rooting depths are similar to previous land cover.	Doorenbos and Pruitt 1977
WI10	Land cover and land use	+	Potential for legumes to be used as cover crops over winter.	
WI11	Biodiversity	+	Increased diversity.	Jensen & Hauggaard-Nielsen 2003
WI12	Animal health and welfare	0	No evidence found, unlikely to be a significant impact.	
WI13	Crop health	+	Increased use of break-crops in the rotations and thus reduce the survival of pests and pathogens is likely, though this effect will depend on the crops involved.	Jensen & Hauggaard-Nielsen 2003
WI14	Household income	0	On a rotation basis, farmers' income is unlikely to be affected. Nevertheless, it is perceived that growing grain legumes is a riskier crop to grow and may not be profitable for them. Income distribution: no significant impact is expected.	Reckling *et al.* 2016a
WI15	Consumer and producer surplus	0	No evidence found, unlikely to be a significant impact.	
WI16	Employment	0	No evidence found, unlikely to be a significant impact.	
WI17	Resource efficiency	+	Reduced use of synthetic nitrogen fertilisers.	
WI18	Human health	0	No evidence found, unlikely to be a significant impact.	
WI19	Social impacts	0	No evidence found, unlikely to be a significant impact.	

Mitigation option:		Incorporating legumes in grass mixes and crop rotations (MO6)		
Impact		Direction/ magnitude	Notes	References
WI20	Cultural impacts	0	No evidence found, unlikely to be a significant impact.	

A1.7 Optimising the use of mineral nitrogen fertilizer (MO7)

Optimising the use of mineral nitrogen fertiliser is assumed to mean that the fertiliser will be used more efficiently and therefore the losses from the system will be reduced. As well as reducing fertiliser applications rates, optimising the use of mineral fertiliser could also result from the optimising the method of applications.

Table 24 Wider impacts of MO7

Mitigation option:		Optimising the use of mineral nitrogen fertilizer (MO7)		
Impact		Direction/ magnitude	Notes	References
WI1	Air quality: NH_3	+	Optimising the application of mineral fertilisers will reduce the emissions of NH_3. Emissions are dependent on fertiliser type, weather and soil conditions. In general applying with a regard to rates, times and placement, improved crop nitrogen uptake will mitigate NH_3 emissions, with minimal increases via the other loss pathways (e.g. nitrate leaching, denitrification to N_2O). Optimizing the method of spreading can also decrease NH_3 emissions e.g. • decreasing the surface area of urea based fertilisers through band application, injection, incorporation • decreasing the time that emissions can take place, i.e. through rapid incorporation or via irrigation; • decreasing the source strength of the emitting surface, i.e. through urease inhibitors • applying under cooler conditions and prior to rainfall (noting to avoid run-off) are associated with lower NH_3 emissions. • Avoiding the application of fertilisers straight after grass cutting Emissions of NH_3 from urea-based fertilisers (5%–40% nitrogen loss as NH_3) are much greater than from other fertiliser types (e.g. ammonium nitrate, 0.5%–5% nitrogen loss as NH_3) due to an increase in pH.	Bittman *et al.* 2014

Mitigation option: Impact		Optimising the use of mineral nitrogen fertilizer (MO7) Direction/ magnitude	Notes	References
			Switching from urea to ammonium nitrate fertiliser will reduce NH_3 emissions, with an effectiveness of around 90%. However, N_2O emissions might increase, especially when the ammonium-nitrate-based fertilisers are applied to moist or wet soils.	
WI2	Air quality: NO_x	+	Reduction of NO_x emissions from fertiliser production and from soil, as a result of reduced nitrogen fertiliser applications.	Pacyna *et al.* 1991, Skiba *et al.* 1997
WI3	Air quality: PM	+	Indirect benefits resulting from the reduced nitrogen fertiliser production process, as reduced NH_3 emissions results in less secondary PM formation. Also reduced NH_3 losses from soils resulting in reduced PM formation.	Sutton ed. 2011
WI4	Air quality: other	0	No evidence found, unlikely to be a significant impact.	
WI5	Water quality: Nitrogen leaching	+	Nutrient use efficiency will be improved. This potentially leads to reduced nitrogen leaching due to reduced fertiliser losses (result of reduced fertiliser application and/or optimised application techniques).	Goulding *et al.* 2008
WI6	Water quality: Phosphorous	+	Nutrient use efficiency will be improved. This potentially leads to reduced multi-nutrient fertiliser applications and/or reduced losses due to optimised application techniques resulting in reduced losses.	Goulding *et al.* 2008
WI7	Water quality: other	0	No evidence found, unlikely to be a significant impact.	
WI8	Soil quality	0	No evidence found, unlikely to be a significant impact.	
WI9	Flood management, water use	0	No evidence found, unlikely to be a significant impact.	
WI10	Land cover and land use	0	No evidence found, unlikely to be a significant impact.	
WI11	Biodiversity	0	Unlikely to be an impact. Small indirect positive effect though reduced nitrogen emissions to air and water is expected.	
WI12	Animal health and welfare	0	No evidence found, unlikely to be a significant impact.	
WI13	Crop health	0	Unlikely to be an impact as it is likely to be a relatively small change in fertiliser applications. If fertiliser applications were to be reduced by 30-50%, there would probably be a negative effect on yield.	

Mitigation option: Impact		Optimising the use of mineral nitrogen fertilizer (MO7) Direction/ magnitude	Notes	References
WI14	Household income	0	The net impact from fertiliser savings and time and money spent on advice/decision support tools/etc. can be either positive or negative, but it is likely to be insignificant.	Eory *et al.* 2015
WI15	Consumer and producer surplus	0	No evidence found, unlikely to be a significant impact.	
WI16	Employment	0	No evidence found, unlikely to be a significant impact.	
WI17	Resource efficiency	0	The impact is highly uncertain as it will be affected by the utilisation of soil mineral, and any marginal changes in the nitrogen offtake.	
WI18	Human health	+	Potential benefits resulting from reduced nutrient loss to air and water.	
WI19	Social impacts	0	No evidence found, unlikely to be a significant impact.	
WI20	Cultural impacts	0	No evidence found, unlikely to be a significant impact.	

A1.8 Low-emission storage and application of manure (MO8)

Low emission storage of manure reduces NH_3 (providing savings in indirect N_2O emissions) and CH_4 emissions via various methods, like reduced contact with air, reduced temperature or reduced pH. Low-emission manure spreading technologies ensure minimal contact of the manure with air, therefore reducing NH_3 emissions. The retained Nitrogen during low-emission storage could increase NH_3 and N_2O losses when applied to the soil unless low-emission spreading techniques are implemented.

Table 25 Wider impacts of MO8

Mitigation option: Impact		Low-emission storage and application of organic fertiliser (MO8) Direction/ magnitude	Notes	References
WI1	Air quality: NH_3	++	Reduced with: band spreaders, injection and rapid incorporation. Slurry store covers can reduce NH_3 by 40-80%. Taller, narrower tanks (and deeper lagoons) have a lower surface area: volume ratio, which reduces NH_3. This also reduces the size and cost of covers, but increases the cost of storage as it increases the wall area and thickness. Slurry acidification reduces NH_3 but may present odour and human health risks.	NAAC 2010, Bittman *et al.* 2014 Van der Zaag *et al.* 2015

Mitigation option: Impact		Low-emission storage and application of organic fertiliser (MO8) Direction/ magnitude	Notes	References
WI2	Air quality: NO_x	0	No evidence found, unlikely to be a significant impact.	
WI3	Air quality: PM	+	Reduced NH_3 emissions results in less secondary PM formation.	Sutton ed. 2011
WI4	Air quality: other	+ -	Reduced odour with band spreaders, injection and rapid incorporation. Most manure covers reduce odour. Slurry acidification may increase odour.	NAAC 2010, Van der Zaag *et al.* 2015
WI5	Water quality: Nitrogen leaching	+	Reduced with band spreaders, injection and rapid incorporation, but shallow injection can increase leaching on some soil types	NAAC 2010, Natural England 2015
WI6	Water quality: Phosphorous	+	Slurry injection and trailing shoe spreading reduce phosphorous losses.	Uusi-Kamppa and Heinonen-Tanski 2008, McConnell *et al.* 2013
WI7	Water quality: other	+	Slurry injection reduces the runoff of faecal microorganisms.	Uusi-Kamppa and Heinonen-Tanski 2008
WI8	Soil quality	+ -	Reduced soil compaction with umbilical systems. Slurry acidification may reduce soil pH (pers comm).	NAAC 2010
WI9	Flood management, water use	0	Minimal effects possible via changed soil structure, affecting infiltration and soil water conveyance.	Amrakh *et al.* 2016
WI10	Land cover and land use	0	No evidence found, unlikely to be a significant impact.	
WI11	Biodiversity	0	No direct on-farm biodiversity effect is expected. Indirect positive effect though reduced air pollution is expected.	
WI12	Animal health and welfare	+	Health effect from reduced pasture contamination with band spreading.	NAAC 2010
WI13	Crop health	0	No evidence found, unlikely to be a significant impact.	
WI14	Household income	+/-	Farmers' income might be positively or negatively impacted (cost of equipment and operation versus reduced need for nitrogen fertiliers, reduced rainwater in the tanks if they are covered with an impermeable cover and reduced crop contamination with more precise manure application. Income distribution: no significant impact is expected.	Frelih-Larsen *et al.* 2014, Weiske *et al.* 2006, Van der Zaag *et al.* 2015
WI15	Consumer and producer surplus	0	No evidence found, unlikely to be a significant impact.	
WI16	Employment	+	No evidence found, a small positive	

Mitigation option: Impact		Low-emission storage and application of organic fertiliser (MO8) Direction/ magnitude	Notes	References
			impact is possible in the form of higher skilled jobs required due to increased technical complexity of the methods.	
WI17	Resource efficiency	+ -	Reduced NH_3 lead to increased nitrogen retention and lower requirement for synthetic nitrogen. Slurry acidification may increase corrosion rates and shorten life of slurry tanks (pers comm 2016).	
WI18	Human health	- +	Slurry acidification may increase risk to farmers, via exposure to strong acids and H_2S. Potential benefits resulting from reduced nutrient loss to air and water.	Van der Zaag *et al.* 2015
WI19	Social impacts	0	No evidence found, unlikely to be a significant impact.	
WI20	Cultural impacts	0	No evidence found, unlikely to be a significant impact.	

A1.9 Improving livestock health (MO9)

Diseases can lead to impacts on livestock performance such as (Skuce *et al.* 2016): (i) fewer units of product e.g. milk, meat or wool; (ii) animals taking longer to reach their target market weight; (iii) delayed onset and reduced quality of production e.g., for milk; (iv) lost production i.e. lambs or calves aborted due to infection; (v) premature culling; (vi) waste of animal products condemned at abattoir; (vii) reduced reproductive performance; or (viii) premature death of animals. Treating and preventing diseases therefore tend to increase productivity and lead to decreases in the emissions intensity of the meat, milk or eggs. For example, treating for diseases that affect feed conversion efficiency (such as liver fluke and parasitic gastroenteritis) will lead to a reduction in the amount of feed consumed and the amount of volatile solids and nitrogen excreted per kg of output, which will in turn reduce emissions associated with feed production and manure management. Health can be improved through preventative controls (such as changing housing and management to reduce stress and exposure to pathogens, vaccination, improved screening and biosecurity, disease vector control) and curative treatments such as antiparasitics and antibiotics. The wider impacts of improving livestock health therefore depend on the specific species, system and, health challenge and control option. The table below seeks to illustrate the wider impacts that could arise from improving health, rather than provide a comprehensive analysis.

Table 26 Wider impacts of MO9

Mitigation option:		Improving livestock health (MO9)		
Impact		**Direction/ magnitude**	**Notes**	**References**
WI1	Air quality: NH_3	+	Measures that improve feed conversion efficiency (either at the animal or flock/herd level) will reduce the amount of nitrogen excreted per kg of meat/milk/eggs produced, leading to reductions in NH_3 from manure management and direct deposition of nitrogen. Examples of diseases with a significant impact on feed conversion efficiency include fasciolosis and parasitic gastroenteritis (see Skuce *et al.* 2016, Annex 2).	Skuce *et al.* 2016
WI2	Air quality: NO_x	0	No evidence found, unlikely to be a significant impact.	
WI3	Air quality: PM	0	No evidence found, unlikely to be a significant impact.	
WI4	Air quality: other	0	No evidence found, unlikely to be a significant impact.	
WI5	Water quality: Nitrogen leaching	+	See NH_3	
WI6	Water quality: Phosphorous	+	Measures that improve feed conversion efficiency (either at the animal or flock/herd level) will reduce the amount of phosphorous excreted per kg of meat/milk/eggs produced.	Skuce *et al.* 2016
WI7	Water quality: other	-	Potential issues of aquatic ecotoxicity with some measures, e.g. SP dips.	Beynon 2012
WI8	Soil quality	0	No evidence found, unlikely to be a significant impact.	
WI9	Flood management, water use	0	No evidence found, unlikely to be a significant impact.	
WI10	Land cover and land use	0	No evidence found, unlikely to be a significant impact.	
WI11	Biodiversity	-	Potential negative impacts via control of wild animal/plants and habitat alteration to reduce vector/pathogen populations (e.g. badger culling to reduce TB transmission or field drainage to reduce mud snail populations, which act as a vector for liver fluke). Further negative impacts of medication to dung invertebrates and indirect impacts further up the food chain.	SCOPS 2016 Adler *et al.* 2016 http://www.drbeynonsbugfarm.com/CMSDocuments//Fact%20sheet%202_Parasiticides_Aug%202016.pdf

Mitigation option: Impact		Improving livestock health (MO9) Direction/ magnitude	Notes	References
WI12	Animal health and welfare	+/-	Most measures should lead to improved animal welfare, however there are potential inter-temporal effects – over use of antimicrobials could lead to resistance and reduced treatment efficacy in the future.	Oliver *et al.* 2011
WI13	Crop health	0	No evidence found, unlikely to be a significant impact.	
WI14	Household income	0	Farmers' income: No significant impact expected in general, though cases might vary widely depending on the disease, treatment and transfer payments. Income distribution: no significant impact is expected.	
WI15	Consumer and producer surplus	0	No significant impact expected in general, though cases might vary widely depending on the disease, treatment and transfer payments.	
WI16	Employment	0	No evidence found, unlikely to be a significant impact.	
WI17	Resource efficiency	+	Improved health should lead to improved resource use efficiency.	
WI18	Human health	+/-	Negative impact via increased antimicrobial resistance. Potential positive impact via reduced human exposure to zoonoses (e.g. salmonella, toxoplasmosis, chlamydia).	Oliver *et al.* 2011
WI19	Social impacts	0	No evidence found, unlikely to be a significant impact.	
WI20	Cultural impacts	0	No evidence found, unlikely to be a significant impact.	

A1.10 Reduced livestock product consumption (MO10)

Reduced livestock product consumption can contribute to GHG mitigation as livestock products are the most GHG intensive components of the diet (Steinfeld *et al.* 2006). Diet related emissions of UK high meat-eaters were found to be 28%, 54%, 84%, 89% and 149% higher than medium meat-eaters, low meat-eaters, fish-eaters, vegetarians and vegans, respectively (Scarborough *et al.* 2014).

Assuming no change in exports, GHG emissions (including UK and overseas emissions) would be reduced by 19% with a 50% reduction in livestock consumption in the UK (-40% dairy, -64% meat) (Audsley *et al.* 2011). That paper reported that net effect would greatly depend on the alternative land use and the substitution in the diet. Substitution of red meat with white meat could reduce emissions by 9%, while reducing white meat consumption by 50% would mitigate 3.3% of the related GHG emissions. At the same time reducing livestock product consumption by 50% would decrease the land area used for food production domestically and overseas by 28-48%, mostly releasing UK grassland areas from food production. If the red meat in the diet were replaced with white meat, the grassland area would be reduced somewhat further, but the increased demand for tillable land both in the UK and abroad would overweight this gain, in total releasing 25-44% land. Reducing white meat consumption only would have only a minor positive effect on land use. The study estimated that currently 36% of the UK food consumption related GHG emissions occur overseas. With the study's assumption on constant proportion of production, exports and imports most of the GHG effects happened in the UK.

However, due to exports and imports, some of the GHG mitigation would manifest abroad. The gross value added of agriculture and food manufacturing (not including wholesale, retail and catering) was £5.4bn in 2014 (Office for National Statistics 2015), while in 2010 food exports and food imports were £4.5bn and £1.1bn, respectively (the former including £4bn drink export) (Scottish Government 2012). 47% of the Scottish primary produce (agriculture and fishery) was purchased by non-Scottish purchasers (including rest of the UK) (Scottish Government 2012). These statistics show that trade with the rest of the UK and abroad is important for the Scottish agricultural and food sector, though these numbers do not reveal how a shift in consumption patterns would impact on exports, imports and ultimately on domestic production.

The domestic environmental impacts and GHG effects of reduced livestock product consumption are dependent on the strength of the relationship between domestic consumption and domestic production. For example, domestic production might be less affected by reduced livestock consumption if export markets for livestock products are available and most of the increase in fruit and vegetable consumption would be provided by imports. Though consumption based environmental metrics are likely to change significantly with a change in the diet, a large proportion of these impacts might manifest abroad, leaving the wider impacts related to domestic production less affected. Wolf *et al.* (2011) modelled three alternative, reduced meat diets for Europe and found that though first order effects include, amongst other changes, a drop of 44% in cattle production, second order effects only show a 9% reduction. Similar effects can be seen in GHG mitigation and in all other environmental impacts analysed, just as in a similar study by Tukker *et al.* (2011).

One of the major co-benefit of reduced meat and dairy product consumption can be improved human health (McMichael *et al.* 2006). However, it is important to note that a healthy diet is not necessarily associated with lower GHG emissions, as the overall GHG effect depend on the substitutions made and the total calorie intake goals. Vieux *et al.* found (2012) that an isocaloric substitution of meat consumption (capping it at 50g day^{-1}) with vegetables and fruits did not reduce the GHG emissions in France, and analysing dietary recommendations in the United States showed that following the 2010 US Dietary Guidelines (even with a reduced total caloric intake) would increase GHG emissions (Tom *et al.* 2015).

Summarising, the domestic GHG and environmental impacts and health impacts of this MO will heavily depend on:

- The reduction in livestock product consumption regarding changes in the share of dairy, white meat and read meat products,
- Whether calorie intake is reduced as well or not,
- Substitution of the livestock products with cereals, vegetables, fruits, oils/nuts/seeds, etc. (with particular attention to products which might have negative environmental impacts, like palm oil and soya, or can be less healthy, like more processed food),
- Reaction of exports, imports and domestic production to consumption change,
- Alternative use of released land and
- Re-structuring of the supply chain in order to reduce negative economic impacts.

Table 27 Wider impacts of MO10

Mitigation option:		**Reduced livestock product consumption (MO10)**		
Impact		**Direction/ magnitude**	**Notes**	**References**
WI1	Air quality: NH_3	+	Acidification and eutrophication are reduced with healthy diets in Europe due to reduced nitrogen pollution; when only income effects are included the benefits are much higher than when second order rebounds (economy-wide reactions on change in demand for foodstuffs)	Tukker *et al.* 2011 Westhoek *et*

Mitigation option: Impact		Reduced livestock product consumption (MO10) Direction/ magnitude	Notes	References
			are considered. Isocaloric replacement of 25-50% of livestock consumption with plant-based products in the EU would reduce nitrogen emissions by 40%.	*al.* 2014
WI2	Air quality: NO_x	0	No evidence found, effects can depend on substitution (as related to transport and processing).	
WI3	Air quality: PM	0	No evidence found, effects can depend on substitution (as related to transport and processing).	
WI4	Air quality: other	0	No evidence found, unlikely to be a significant impact.	
WI5	Water quality: Nitrogen leaching	+	Acidification and eutrophication are reduced with healthy diets in Europe; when only income effects are included the benefits are much higher than when second order rebounds (economy-wide reactions on change in demand for foodstuffs) are considered.	Tukker *et al.* 2011
WI6	Water quality: Phosphorous	+	Acidification and eutrophication are reduced with healthy diets in Europe; when only income effects are included the benefits are much higher than when second order rebounds (economy-wide reactions on change in demand for foodstuffs) are considered.	Tukker *et al.* 2011
WI7	Water quality: other	-	Ecotoxicity (mostly related to pesticide use from higher consumption of vegetable food) increases with healthier diets in Europe.	Tukker *et al.* 2011
WI8	Soil quality	+/-	No evidence found, impacts would greatly depend on alternative use.	
WI9	Flood management, water use	+/-	The impact on water scarcity varies depending on the diet, though most of the impact happens outwit of the UK (not including knock-on effect on land use)	Hess *et al.* 2015
WI10	Land cover and land use	+	Isocaloric replacement of 25-50% of livestock consumption with plant-based products in the EU would reduce per capita land use by 23%. In Scotland the most substantial impact would be a move from grasslands towards alternative uses (e.g. forestry).	Westhoek *et al.* 2014

Mitigation option: Impact		Reduced livestock product consumption (MO10) Direction/ magnitude	Notes	References
WI11	Biodiversity	+/-	No evidence found, impacts would greatly depend on what land areas will be released (e.g. extensive or intensive grasslands, arable land) and on the alternative use (e.g. sustainable forestry, arable production or bioenergy production).	
WI12	Animal health and welfare	+/-	No evidence found. The effect could depend on consumer demand for animal welfare and the economics of intensification *vs* extensification of livestock production.	
WI13	Crop health	0	No evidence found, unlikely to be a significant impact.	
WI14	Household income	+/-	Substituting livestock products with other food products might result either in savings or higher food expenses for the consumers. If GHG emission-based food taxes were introduced, also resulting in lower meat consumption (highest tax rates on beef, coffee drinks, lamb, cheese, animal fats, pork, other meat, bread, tea and cocoa), all socio-economic classes would reduce their food intake, and the tax burden would fall disproportionately on households in the lowest socio-economic class. Household income of those in the livestock supply chain could decrease.	Kehlbacher *et al.* 2016
WI15	Consumer and producer surplus	+/-	The impacts are negative on the livestock related parts of the food chain while positive on producers and processors of plant-based food products and also on some other sectors, like transport. As much of Scotland's agricultural land is only suitable for livestock but not vegetable/grain production, the overall effects – as far as Scottish consumption will affect Scottish production – are more likely to be negative.	Lock *et al.* 2013
WI16	Employment	+/-	No evidence found, likely to follow production changes described in the previous point.	
WI17	Resource efficiency	+	As livestock numbers are reduced	Westhoek *et*

Mitigation option: Impact		Reduced livestock product consumption (MO10) Direction/ magnitude	Notes	References
			part of the ecological pyramid related to human consumption is eliminated, therefore resource use efficiency increases (e.g. nitrogen use efficiency of the European food system can increase from 18% to 41-47%.	*al.* 2014
WI18	Human health	++	Reductions in livestock production consumption leads to 2,000 – 37,000 avoided premature death per annum in the UK, depending on the diet changes (modelled diet scenarios were based on the Committee on Climate Change Fourth Carbon Budget). Population aggregate risks in the UK would be reduced 3% to 12% for coronary heart disease, diabetes mellitus and colorectal cancer if meat consumption is reduced. Following the UK dietary guidelines would avoid 33,000 premature death per annum from cardiovascular diseases and cancer in the UK (4,300 in Scotland). Human toxicity is reduced with healthier diets in Europe.	Scarborough *et al.* 2012a Aston *et al.* 2012 Scarborough *et al.* 2012b Tukker *et al.* 2011
WI19	Social impacts	+/-	No evidence found, effects would depend on larger and smaller scale changes in the food supply chain.	
WI20	Cultural impacts	+/-	No evidence found, effects might arise in food culture and also from the induced land use change.	

A1.11 Afforestation (MO11)

Afforestation has been and can further be a major contributor to reducing the net GHG emissions by sequestering carbon in the soil and as woody biomass.

Forestry practice is covered by the UK Forestry Standard (Forestry Commission 2011). Additionally, the UK Woodland Assurance Standard (UKWAS 2008) contains explicit commitments to low impact silvicultural systems which may include, but is not exclusively restricted to, continuous cover forestry operations. Certification bodies such as the Forestry Stewardship Council and Programme for the Endorsement of Forest Certification also provide accreditation and endorsement of sustainably managed forests. Adherence to standards will ensure that potential adverse impacts are minimised.

Table 28 Wider impacts of MO11

Mitigation option:		**Afforestation (MO11)**		
Impact		**Direction/ magnitude**	**Notes**	**References**
WI1	Air quality: NH_3	++	NH_3 is captured by trees downwind, which can be of particular importance near livestock operations.	Patterson *et al.* 2008, Famulari *et al.* 2015, Bealey *et al.* 2014
WI2	Air quality: NO_x	++	A number of studies from around the world which are transferable to Scotland show that trees can remove NO_x and improve air quality in both urban and rural areas.	Cohen *et al.* 2014, Nowak *et al.* 2006
WI3	Air quality: PM	++	Reduced concentration of PM_{10} (and other pollutants). Coniferous species and broadleaf trees with hairy leaves have a greater effectiveness at capturing particles than other broadleaf trees.	Cohen *et al.* 2014, Powe and Willis 2004 Beckett *et al.* 2000
WI4	Air quality: other	+	Reduced concentration of carbon monoxide and sulphur dioxide. Urban trees generally reduce ozone and carbon monoxide; evidence on similar effects of forests has not been found.	Cohen *et al.* 2014, Powe and Willis 2004 Nowak *et al.* 2000, Nowak *et al.* 2006, Taha 1996
WI5	Water quality: Nitrogen leaching	+	Afforestation of arable land can reduce nitrogen leaching although nitrogen leaching can occur from mature forests which have achieved full canopy cover. The amount of nitrogen leaching depends on tree type, with higher leaching rates from broadleaf woodland. Harvesting can lead to short time releases of nitrogen although this depends on harvest method, and fluxes may be less than from arable land.	Hansen *et al.* 2007, Bastrup-Birk & Gundersen 2004, Reynolds & Edwards 1995 Elberling 2006 Nisbet *et al.* 2011
WI6	Water quality: Phosphorous	0	Tree planting and harvesting have the potential to release	Nisbet *et al.* 2011,

Mitigation option: Impact		Afforestation (MO11) Direction/ magnitude	Notes	References
			Phosphorous into waterbodies, however woodland buffer strips along water courses can reduce erosion and phosphate leaching. Forestry operations are carried on in accordance with the Forest and Water Guidelines it is unlikely to be an effect.	Stevenson *et al.* 2016 Nisbet 2002
WI7	Water quality: other	- 0 - - +	Although afforestation has the potential to produce adverse impacts on water quality, where forests are planted and managed in accordance with the UK Forestry Standard adverse impacts are likely to be avoided. However potential issues associated with afforestation are listed here to highlight the importance of ensuring that the Forest Standard is followed. Changes in algal populations in lakes in Ireland related to afforestation in catchments in Ireland which were more than 20% forested, but no effect on less afforested catchments. No change in turbidity, water colour, or iron or manganese concentrations in water in two afforested catchments in Argyll where forestry operations are carried on in accordance with the Forest and Water Guidelines. Badly located forests, particularly conifers on poorly buffered soils can cause acidification by scavenging atmospheric sulphur and nitrogen. Forests close to rivers can provide shade help rivers to adapt to climate change, but some species can cast heavy shade and lowers water temperature excessively if planted close to river banks. Poor practice during planting and harvesting can release sediment into watercourses. Afforestation around arable fields can reduce spray drift of pesticides into watercourses by 60 – 90 %.	Stevenson *et al.* 2016 Nisbet 2002 Nisbet *et al.* 2011 Nisbet *et al.* 2011 Nisbet *et al.* 2011 Nisbet *et al.* 2011
WI8	Soil quality	+/-	Afforestation on mineral soils can increase soil carbon stocks. However drainage and afforestation of organic soils releases soil carbon. The UK Forestry Standard	Bradley *et al.* 2005, Grüneberg *et al.* 2014

Mitigation option: Impact		Afforestation (MO11) Direction/ magnitude	Notes	References
			does not permit afforestation on organic soils and therefore mitigates this risk.	
WI9	Flood management, water use	++	There is evidence that trees (coniferous to a larger degree than broadleaved) use/intercept more water than shorter vegetation types Infiltration rates may be significantly enhanced (and thus runoff reduced) where grazed pasture is planted with woodland Floodplain woodland may lead to significant increases in flood storage and flood peak travel times	Bosch and Hewlett 1982 Marshall *et al.* 2014 Thomas and Nisbet 2007
WI10	Land cover and land use	+	Afforestation inherently involves a change in land use and in general considered as a positive outcome. However, opportunity costs of the previous land use need to be considered. For example afforestation of prime agricultural land would result of less of agricultural production, whereas afforestation of semi-natural grassland would cause much less loss of existing income. Afforestation alters landscape value. Public perception of landscape change is dependent on the proposed change and knowledge of the previous land use history.	Hanley *et al.* 2009, Habron 1998
WI11	Biodiversity	+/-	The effect on biodiversity will depend on the type of tree planting and the previous use of the afforested land. UK Forestry Standards require the conservation and enhancement of biodiversity in afforestation and forest management.	Forestry Commission 2011
WI12	Animal health and welfare	-	Probably little effect in most instances, although afforestation on peatlands might increase tick abundance.	Gilbert 2013
WI13	Crop health	0	No evidence found, unlikely to be a significant impact.	
WI14	Household income	+/-	Land owners' income: depends on the balance of the opportunity costs of the land and any government payments. Income distribution: Likely to depend on the balance of	

Mitigation option: Impact		Afforestation (MO11) Direction/ magnitude	Notes	References
			employment opportunities associated with afforested land compared to those associated with the previous land use.	
WI15	Consumer and producer surplus	+/-	Will reduce agricultural production, but increase production of timber products.	CJC Consulting 2013
WI16	Employment	+/-	Potential to increase employment in rural Scotland in forestry activities, timber processing and through associated leisure and tourism activities. However will displace some jobs in other land based sectors e.g. agriculture.	CJC Consulting 2013
WI17	Resource efficiency	+	The produced wood can be used for fuel or as construction material.	CJC Consulting 2013
WI18	Human health	+	Woodlands can enhance recreational opportunity, encourage people to exercise more and improve quality of life. Forests provide pest and disease regulation, noise regulation and soil, air and water regulation; all improving contributing to positive human health outcomes. Additionally, woodlands improve physical and mental health via providing recreational space. Woodland has positive impacts on health because it can absorb pollutants, encourage exercise and reduce stress.	Ambrose-Oji *et al.* 2014 Bateman *et al.* 2011 Mourato *et al.* 2010, Nowak *et al.* 2013, Tiwary *et al.* 2009
WI19	Social impacts	+	Woodlands located close to settlements can provide space for community activities.	Ambrose-Oji *et al.* 2014
WI20	Cultural impacts	+/-	Woodlands can enhance recreational opportunity and can contribute to landscape and aesthetic amenity. Recreational demand varies to the nature of the forest recreation site such as the size and type of woodland, facilities and the recreational activities available on site. Woodland also indirectly influences recreation, for example: via effects on water quality, affecting recreational fishing, swimming or boating, air quality (through health effects or visibility), climate/temperature (through	Ambrose-Oji *et al.* 2014, Jones *et al.* 2010, Bateman *et al.* 2011, Forestry Commission 2011

Mitigation option: Impact		Afforestation (MO11) Direction/ magnitude	Notes	References
			shading, cooling and shelter from extreme weather) and biodiversity (through bird watching or nature viewing). Afforestation might negatively impact landscape, historic and recreational values of the land in certain places; afforestation projects should follow the UK Forestry Standards, and "should be designed […] to take account of the historical character and cultural values of the landscape. […] to take account of landscape designations, designed landscapes, historic landscapes and the various policies that apply." Those involved in activities related to the current use of land which is to be afforested may view afforestation as a challenge to the cultures associated with those land uses e.g upland farming and sporting activities.	

A1.12 Peatland restoration (MO12)

Scotland has large areas of peatland which are significant carbon reservoirs, storing 1,780 Mt of carbon (Smith *et al.* 2007). However, land management activities have resulted in 70 % of blanket bog (Artz *et al.* 2014) and 90 % of raised bog in Scotland (Lindsay and Immirzi, 1996) are estimated to be degraded with the result that they have switched from being GHG sinks to GHG sources. Peatland restoration which raises the water table and restores semi-natural vegetation can reduce the CO_2 emissions associated with the degradation of peatlands and may return peatlands to being net GHG sinks. Peatland restoration is likely to improve the biodiversity of these international important habitats and is likely to have complex interactions with hydrology and landscape value.

Table 29 Wider impacts of MO12

Mitigation option: Impact		Peatland restoration (MO12) Direction/ magnitude	Notes	References
WI1	Air quality: NH_3	0	No evidence found, unlikely to be a significant impact.	
WI2	Air quality: NO_x	0	No evidence found, unlikely to be a significant impact.	

Mitigation option: Impact		Peatland restoration (MO12) Direction/ magnitude	Notes	References
WI3	Air quality: PM	+	Could be a small reduction in airborne PM from reduced heather burning and eroding peat.	
WI4	Air quality: other	0	No evidence found, unlikely to be a significant impact.	
WI5	Water quality: Nitrogen leaching	-	Rewetting of peatland sites can increase nitrogen leaching particularly in the early years of restoration. The risk is increased where fertiliser has been applied or where trees are felled during restoration.	Similä *et al.* 2014, Menberu *et al.* 2015, Kieckbusch and Schrautzer 2007
WI6	Water quality: Phosphorous	-	Rewetting of peatland sites can increase phosphorous leaching particularly in the early years of restoration. The risk is increased where fertiliser has been applied or where trees are felled during restoration.	Similä *et al.* 2014, Menberu *et al.* 2015, Kieckbusch and Schrautzer 2007, Cummins and Farrell 2000
WI7	Water quality: other	- +	Rewetting of peatland sites can increase organic carbon leaching, particularly in the early years of restoration. In the longer term peatland restoration can reduce organic carbon leaching in some catchments. Removing dissolved organic carbon from water increases water treatment costs.	Similä *et al.* 2014, Menberu *et al.* 2015, Kieckbusch and Schrautzer 2007 Armstrong *et al.* 2010 Wallage *et al.* 2006
WI8	Soil quality	++	Reduced carbon loss from degraded peat is an intended outcome of peatland restoration.	Lilly, *et al.* 2009
WI9	Flood management, water use	Flood management +/-	Drainage speeds-up flow, which can lower water tables. This increases the ability of the drained area to absorb rainfall, which can help reduce flood risk downstream. Net effects are difficult to measure. Impacts depend on topography, layout of drainage or other management intervention and location in the headwater	Acreman and Holden 2013

Mitigation option: Impact		Peatland restoration (MO12) Direction/ magnitude	Notes	References
		Water use --	catchment with respect to the drainage network. So in some cases blocking peatland drains will reduce flood risk, in other cases it can increase flood risk. Re-vegetating wetlands reduces the speed of overland flow and potentially reduces the flood peak during some events. There is strong evidence that wetlands evaporate more water than other land types, such as forests, savannah grassland or arable land. Many studies of wetlands conclude that wetlands reduce the flow of water in downstream rivers during dry periods (relevant for Scottish dry spells which are likely to become more frequent as a result of climate change).	Bullock and Acreman 2003
WI10	Land cover and land use	+/-	Change from afforested plantation forestry to semi-natural peatland alters landscape value. Public perception of landscape change is dependent on the proposed change and knowledge of the previous land use history. Deforestation limits the use of peatlands for timber production. It allows peatlands to increase carbon sequestration in peat, but this has to be offset against reduced in carbon sequestration in timber.	Hanley *et al.* 2009, Habron 1998
WI11	Biodiversity	++	Scotland holds 13 % of the world's peatlands which are globally important habitats, although 80 % of Scottish peatlands are currently degraded. Near-natural peatlands are protected under the Ramsar convention and the EU habitats Directive. Peatland restoration aims to restore natural peat forming vegetation.	Ramsar 1971
WI12	Animal health and welfare	+	Tick numbers are reduced when afforested peatlands are restored, potentially reducing tick-born diseases in nearby livestock.	Gilbert 2013
WI13	Crop health	-	Could be a small negative effect on crop health if cropland on drained peat was rewetted (not full restoration but higher water table	

Mitigation option: Impact		Peatland restoration (MO12) Direction/ magnitude	Notes	References
			under arable to reduce carbon loss), although more applicable to England than Scotland as the area of cropland on drained peat in Scotland is small (around 8.6 kha) and the focus of peatland restoration is on afforested peat or semi-natural grassland.	
WI14	Household income	+/-	Land owners' income: depends on the balance of the opportunity costs of the land and any government payments. Income distribution: no evidence, and unlikely to be an important impact	
WI15	Consumer and producer surplus	0	No evidence, but the impact might be important. Regarding consumer surplus indirect impacts of restoration on water quality may be worth investigating in more detail – specifically impacts on water treatment costs. Regarding producer surplus, impacts depend on previous land uses, which primarily include forestry, grouse and deer management, grazing of livestock (sheep). Impacts will depend on the scale of restoration and other local factors. There is anecdotal evidence that land managers have opted for restoring parts of their lands because of positive side-effects on production-related activities (Andrew McBride, personal comm. 6 June 2016). For example, blocking drains and gullies may decrease mortality rates amongst grouse chicks. Hence, the assumption of positive opportunity costs of restoration may not hold in all cases and requires further investigation.	Glenk *et al.* 2014
WI16	Employment	0	No evidence found, unlikely to be a significant impact.	
WI17	Resource efficiency	0	No evidence found, unlikely to be a significant impact.	
WI18	Human health	+/-	Human health may benefit from reduced tick numbers, particularly with the increasing prevalence of the tick-borne infection Lyme's disease. Increased incidence of midges is possible if restoration takes place in	Gilbert 2013

Mitigation option: Impact		Peatland restoration (MO12) Direction/ magnitude	Notes	References
			proximity to popular camping grounds or hiking paths. Impacts on health may also be related to recreational opportunities.	Martin-Ortega *et al.* 2014
WI19	Social impacts	+	No evidence found, but the impact might be important, especially for rural communities that engage in peatland restoration activities, as well as communities that have strong traditional ties to peatlands (e.g. crofting communities)	
WI20	Cultural impacts	+/-	No evidence, but the impact might be important. Peatlands provide important cultural services, though the current provision of these services cannot be easily transferred to assess the impacts that peatland restoration will have. E.g. hunting is an important benefit currently but restoration via reduced burning activities may be detrimental to this activity. Accessibility might be an important factor in recreational benefits.	

Appendix A2. Review of models and tools for quantitative assessment of the wider impacts of ALULUCF GHG mitigation options

A2.1 Models and tools for air quality (WI1-WI4)

The models described for assessing air quality focuses on a combination of air dispersion models (EMEP4UK, SCAIL) which can output deposition and concentrations values to a grid or receptor, and an integrated model which can explore abatement scenarios and provide benchmarks for protection of ecosystems and air quality and human health (UKIAM, GAINS). DNDC is a process based model which predicts crop yield, carbon sequestration, nitrate leaching loss, and emissions of carbon and nitrogen gases in agroecosystems. Most of the MOs outlined in this report can be assessed by way of altering input emissions to the models. The models can be used to explore national and local scale effects, although the models are restricted down to a resolution at the 1km scale (EMEP4UK, UKIAM). However, individual local scale modelling can be carried out by models such as SCAIL to assess source to receptor impacts at the farm level.

A2.1.1 EMEP4UK

Table 30 Model description: EMEP4UK

Model/tool name	**EMEP4UK**	**References**
Impacts assessed	Air pollutants	
Sectors covered	Agriculture, industry, transport, stationary combustion (all emission sectors)	
Geographical scope	Country/Regional	
Modelling approach	The EMEP4UK model is a 3D eulerian atmospheric chemistry transport model (ACTM) driven by the numerical weather prediction model weather and research forecast (WRF). The model is used to simulate photo oxidants and both inorganic and organic aerosols. The EMEP4UK model calculates hourly to annual average tropospheric atmospheric composition and deposition of various pollutants; including speciated components of PM_{10}, $PM_{2.5}$, secondary organic aerosols (SOA), elemental carbon (EC), secondary inorganic aerosols (SIA), sulphur dioxide, NH_3, NO_x, and ozone. Dry and wet	Vieno *et al.* 2010 Simpson *et al.* 2012

Model/tool name	EMEP4UK	References
	deposition of pollutants are routinely calculated by the model. EMEP4UK initially was developed as a regional application of the EMEP MSc-W model which is used to support the Convention on Long Range Transboundary Air Pollution (CLRTAP). However, now the EMEP4xyz can be apply virtually anywhere in the world from Global run to nested regions at high resolutions.	
Main model outputs	UK pollutant maps (up to 1km x 1km grid) e.g. https://eip.ceh.ac.uk/apps/atmospheric http://www.emep4uk.ceh.ac.uk/2014	
Main data needs	Country/Global emission inventory Driven by real meteorology, therefore an EMEP compatible meteorological dataset is required. The EMEP4UK rv4.8 currently uses the WRF model version 3.7.1 (Weather Research and Forecasting) as meteorological driver.	
Main limitations	Level of expertise to run and making scenarios into emission maps.	
Validation/ robustness	EMEP4UK has been compared with other models. Also validated with measurement networks. The EMEP MSC-W model is extensively validated and verified and the model performances are reported annually in the EMEP status report. http://emep.int/publ/emep2016_publications.html.	Carslaw *et al.* 2011a Carslaw *et al.* 2011b Dore *et al.* 2015 Vieno *et al.* 2010 Vieno *et al.* 2014 Vieno *et al.* 2016a
Scottish/UK case study examples	EMEP4UK has been used to model: Ozone during a summer heat wave Multiple years UK atmospheric composition PM air episodes PM2.5 mitigation	 Vieno *et al.* 2010 Vieno *et al.* 2014 Vieno *et al.* 2016a Vieno *et al.* 2016b
Examples of integrated use	The EMEP-MSc-W model has been integrated with the GAINS model	Simpson *et al.* 2012

A2.1.2 UKIAM

Table 31 Model description: UKIAM

Model/tool name	UKIAM (UK Integrated Assessment Model)	References
Impacts assessed	An integrated assessment modelling tool to support policy in relation to air pollutants and GHGs.	
Sectors covered	Agriculture, industry, transport – all sectors Pollutants covered: sulphur dioxide, NO_x, PM, NH_3. UKIAM has also been extended to include GHG emissions.	ApSimon *et al.* 2009
Geographical scope	UK and regional	
Modelling approach	UKIAM projects UK emissions for sulphur dioxide, NO_x, NH_3, PM_{10} and $PM_{2.5}$ for future scenarios providing data on pollutant deposition, criteria for ecosystem protection, urban air quality and human health and data on potential	Oxley *et al.* 2003, Oxley *et al.* 2013

Model/tool name	UKIAM (UK Integrated Assessment Model)	References
	emission abatement measures. UKIAM uses pre-calculated source–receptor matrices derived from atmospheric modelling to estimate the response of baseline concentrations and deposition to changes in different sources both within and outside the UK. Abatement measures have been defined and incorporated into a Multi-Pollutant Measures Database giving percentage reductions in emissions achieved for each pollutant for a selected source, together with unit costs. UKIAM remains an independent model paralleling GAINS but model at 1 to 5 km resolution over the UK using the FRAME model.	Oxley *et al.* 2013, AMEC 2009 Dore *et al.* 2007, Fournier *et al.* 2004
Main model outputs	Cost data analysis tables, deposition maps.	
Main data needs	Emissions inventories and scenarios	
Main limitations	Time consideration need to be given for the multiple model runs.	
Validation/ robustness	Model output from FRAME have been validated against measurements and compared with other models. In general, it is less easy to validate modelled data on source attribution of pollutant concentrations and deposition against measurements.	Dore *et al.* 2015
Scottish/UK case study examples	PM2.5 emission abatement strategies and sensitivity to human health (in London). UK assessment of traffic emissions and future scenarios and the UK's air quality strategy.	Oxley *et al.* 2015 Oxley *et al.* 2011
Examples of integrated use	Already an integrated model	

A2.1.3 DNDC

Table 32 Model description: DNDC

Model/tool name	DNDC (Denitrification-Decomposition model)	References
Impacts assessed	Predicts crop yield, carbon sequestration, nitrate leaching loss, and emissions of carbon and nitrogen gases in agroecosystems.	
Sectors covered	Agriculture	
Geographical scope	Site or regional	
Modelling approach	DNDC is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agroecosystems. The entire model is driven by four primary ecological drivers, namely climate, soil, vegetation, and management practices. The model consists of two components: 1. Soil climate, crop growth and decomposition sub-models. Predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles. These are driven by ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity).	Gilhespy *et al.* 2014

Model/tool name	DNDC (Denitrification-Decomposition model)	References
	2. Nitrification, denitrification and fermentation sub-models. Predicts emissions of CO_2, CH_4, NH_3, nitric oxide, N_2O and dinitrogen from the plant-soil systems. DNDC has been modified for application into the UK to produce UK-DNDC, and which was updated. It uses UK-specific input data. At the regional scale, UK-DNDC utilises its own databases. Manure-DNDC represents the manure life cycle on farms and predict GHG and NH_3 emissions from livestock manure systems. http://www.dndc.sr.unh.edu/model/GuideDNDC95.pdf	Brown *et al.* 2002 Cardenas *et al.* 2013 Li *et al.* 2012
Main model outputs	Simulated results including daily and annual crop biomass, carbon and nitrogen pools/fluxes, water budget and daily fluxes of NH_3, CH_4, N_2O, nitric oxide, and dinitrogen. These are recorded in a series of files (csv).	
Main data needs	3 main datasets are required: 1. Crop management parameters inputs are required (e.g. crop type, rotation, tillage, fertilization, irrigation etc.). 2. Climate data for the years to be simulated should be provided (temperature, precipitation are required, additional data e.g. wind speed, solar radiation and relative humility can be provided). 3. Soil parameters include texture, bulk density, pH etc. Background concentrations of NH_3 and CO_2 can also be set.	
Main limitations	Large data input requirements	
Validation/ robustness	DNDC has now been used to simulate various cropping, grazing and forest systems in many countries. The agreement between the model simulations and measured values vary, with some studies reporting poor agreement.	Giltrap *et al.* 2010
Scottish/UK case study examples	N_2O emissions from soils at county level for the UK. Four MOs were assessed and the results showed there were differences in the emission factors according to location.	Cardenas *et al.* 2013
Examples of integrated use	DNDC has been developed into various other sub-models: Wetland-DNDC, Forest-DNDC, CAPRI-DNDC. The INTEGRATOR model uses CAPRI-DNDC.	Gilhespy *et al.* 2014 De Vries *et al.* 2011

A2.1.4 GAINS

Table 33 Model description: GAINS

Model/tool name	GAINS (The Greenhouse gas –Air pollution INteractions and Synergies)	References
Impacts assessed	Estimates the environmental effects of air pollution under consideration of GHG emissions. The model simulates the flow of pollutants from their sources to their multiple effects, and estimates costs and impacts of	Amann *et al.* 2011a Klimont & Winiwarter 2014

Model/tool name	GAINS (The Greenhouse gas –Air pollution INteractions and Synergies)	References
	policy interventions. Assesses economic sectors and options for emission control, costs of implementation in terms of reducing ecosystem and human health impacts. GAINS agriculture: An NH_3 module for GAINS has been developed for NH_3 emissions from animal manure at 4 stages – housing, storage, application and grazing. Emission factors and a set of abatement measures are defined for each stage.	
Sectors covered	Agriculture, Industry, Transport Pollutants covered: sulphur dioxide, NO_x, volatile organic acid, PM, NH_3, CO_2, CH_4, N_2O.	
Geographical scope	Individual countries, regions and global	
Modelling approach	Cost-benefit source-receptor model taking into account atmospheric chemistry, quantification of ecosystem and human health responses	
Main model outputs	Cost data analysis tables, deposition maps.	
Main data needs	Cost data (investment costs, operating costs (fixed & variable)), future scenarios & baseline projections of economic activities.	
Main limitations	Dependent on complete emission inventories	
Validation/ robustness	No information	
Scottish/UK case study examples	EU member states including UK. Outputs included: Health impact indicators, critical load exceedance for nitrogen and acidification.	Amann *et al.* 2011b
Examples of integrated use	Various assessments of EU and UNECE policies, e.g. National Emission Ceilings Directive, Gothenburg Protocol	

A2.1.5 MODDAS-THETIS

Table 34 Model description: MODDAS-THETIS

Model/tool name	MODDAS-THETIS	References
Impacts assessed	Estimates the pollutant recapture by trees for NH_3 and PM	
Sectors covered	Agriculture (NH_3) and combustion sources (PM)	
Geographical scope	Site based assessments (single source)	
Modelling approach	MODDAS-THETIS is a flexible two-dimensional (along wind and vertical) model that can be used to examine the pollutant abatement potential of tree shelter-belt structures in the landscape. MODDAS is a Lagrangian stochastic model for gaseous dispersion and THETIS is turbulence model designed for transfer within the planetary boundary layer as well as within a plant canopy. The model scenario setup is based around a woodland schema where different blocks of canopy are designed of varying height and width and density (Leaf Area Index - LAI). Source strength and the source length can also	Loubet *et al.* 2006 Foudhil 2005 Bealey *et al.* 2014

Model/tool name	MODDAS-THETIS	References
	be configured.	
Main model outputs	Data table of pollutant recapture % Concentrations and deposition plots - before, within and after the canopy.	
Main data needs	Source emissions	
Main limitations	Can only be used for single sources	
Validation/ robustness	Both models have been validated in conditions similar to those modelled here, specifically MODDAS in an NH_3 release experiment over a developed maize canopy and a grassland, and THETIS over several canopy arrangements.	Loubet *et al.* 2006, Foudhil 2005 Dupont and Brunet, 2006
Scottish/UK case study examples	No real-life scenarios applied as yet. Modelling of a housing scenario showed that a 30-50 m deep tree shelter belt could capture up to 15-20% of the NH_3 emitted.	Bealey *et al.* 2014
Examples of integrated use	Not yet.	

A2.1.6 SCAIL

Table 35 Model description: SCAIL

Model/tool name	SCAIL (Simple Calculation of Atmospheric Impact Limits)	References
Impacts assessed	Estimates concentrations and deposition from local sources	
Sectors covered	Agriculture (NH_3, nitrogen and acid deposition, PM) and combustion sources (NO_x, sulphur dioxide, nitrogen and acid deposition, PM)	
Geographical scope	Site based assessments (multi-sources)	
Modelling approach	SCAIL is a suite of screening tools for assessing the impact from agricultural and combustion sources on semi-natural areas like SSSIs and SACs. SCAIL provides an estimate of the amount of acidity, nitrogen or sulphur deposited to an ecosystem. Meteorology in the model is provided by 40 meteorological stations around the UK SCAIL uses the air dispersion model Aermod.	Hill *et al.* 2014a www.scail.ceh.ac.uk
Main model outputs	Data table of source contribution to pollutant concentration and deposition. Provides critical load exceedance statistic for ecosystems	
Main data needs	Background concentration and deposition maps Meteorological data (wind speed, wind direction) Emission, livestock numbers, storage/spreading volumes etc	
Main limitations	Only for use in local site-based assessments	
Validation/ robustness	SCAIL has been validated against measurements taken around farms and anaerobic digesters. Provides a best estimate for pollutant impacts.	Hill *et al.* 2014b, Bell *et al.* 2016
Scottish/UK case study	Used across UK and in Scotland by SEPA for permitting purposes	

Model/tool name	SCAIL (Simple Calculation of Atmospheric Impact Limits)	References
examples		
Examples of integrated use	Not yet.	

A2.2 Models and tools for water quality (WI5-WI7)

The models selected are able to assess the effects of MOs at at least farm scale, with scope for upscaling to catchment, regional or national scales. All of the models listed have been successfully used in UK studies to assess the wider effects of GHG MOs. The Farmscoper model and the ADAS Wales Framework are related suites of models able to assess the impacts of mitigation measures on a range of pollutants and pathways. The LUCI model is a GIS based ecosystem services model which assess the effects of land use and management and is able to include the effects of afforestation and peatland restoration as well as measures to reduce GHG emissions from agricultural activities. DNDC, mentioned in the previous section (A2.1.3), is also capable of modelling certain water quality impacts.

A2.2.1 ADAS Wales

Table 36 Model description: ADAS Wales

Model/tool name	ADAS Wales Diffuse Pollution Emission Modelling Framework	References
Impacts assessed	Nitrate, phosphorus, sediment, pesticides, veterinary medicines, N_2O, CH_4 and CO_2	Emmett *et al.* 2014
Sectors covered	Agriculture	
Geographical scope	Catchment scale, parameterized for Wales.	
Modelling approach	The framework is similar to the Defra Farmscoper model (see Section A2.2.3), and combines a suite of models to calculate emissions of nitrate, phosphorus, sediment, pesticides, veterinary medicines, N_2O, CH_4 and CO_2. The framework is stratified by Robust Farm Type and reported emissions for each of the Water Framework Directive river catchments in Wales. The modelling framework uses a combination of process based and inventory models. Emissions of pesticides and veterinary medicines are calculated using the regulatory MACRO and PRZM models. Phosphorus and sediment losses are calculated using the PSYCHIC model. Nitrate losses are calculated using the N-CYCLE,	Anthony and Gooday 2010, Emmett *et al.* 2014 Jarvis 1994, Carsel *et al.* 1984 Davison *et al.* 2008 Scholefield *et al.*

Model/tool name	ADAS Wales Diffuse Pollution Emission Modelling Framework	References
	NITCAT and MANNER models. CH_4 and N_2O emissions are calculated using the tier one and two IPCC methodology with modifications to represent the effects of observed levels of soil compaction and poaching on N_2O emissions. Indirect N_2O emissions from leached nitrate were calculated using the appropriate nitrogen leaching model. The framework contains a meta-model of export coefficients derived from process based models describing the effects of 40 individual mitigation methods for pollutant emissions to air and water. The modelling framework provides a consistent assessment of multiple pollutants to air and water from agriculture in Wales, which explicitly links the impact of MOs intended to improve water quality with their secondary impacts on emissions of GHGs.	1991, Lord 1992, Chambers *et al.* 1999 Baggott *et al.* 2006, IPCC 2006
Main model outputs	Emissions of nitrate, phosphorus, sediment, pesticides, veterinary medicines, N_2O, CH_4 and CO_2	
Main data needs	Spatial database of agricultural activity, separated by farm system type. Data on agricultural practices (stocking levels, crop rotations, fertiliser application rates, manure management) and uptake of the mitigation measure e.g. June Agricultural Census, British Survey of Fertiliser Practice and Farm Practice Survey. Water Framework Directive Catchment boundaries. Monthly average rainfall, temperatures and number of rain days on a 5 by 5 km^2 grid. Soil particle size distribution (percentage sand, silt and clay), organic matter content bulk density and HOST class of the dominant soil series within each 1 km^2 squares. Digital Elevation Model. Land cover data. Discharge consents database for non-agricultural pollution inputs.	Anthony *et al.* 2012
Main limitations	Has currently only been developed for Wales, although parameterisation may be similar between Wales and Scotland.	
Validation/ robustness	Gives a consistent framework for using several existing well established models.	
Scottish/UK case study examples	Used to evaluate the effect of Welsh Government Agri-Environment schemes.	Anthony *et al.* 2012
Examples of integrated use	This tool is itself an integrated suite of models. It has been integrated with the LUCI model as part of the Welsh Government Glastir Monitoring and Evaluation Programme. The Farmscoper model incorporates a similar suite of models to the ADAS Wales model but also includes additional models to assess emissions of NH_3. Farmscoper integrates emission data with unit costings for measure implementation in an algorithm which	Emmett *et al.* 2014 Anthony and Gooday 2010

Model/tool name	ADAS Wales Diffuse Pollution Emission Modelling Framework	References
	optimizes measures to maximize benefits for the range of wider impacts.	

A2.2.2 LUCI

Table 37 Model description: LUCI

Model/tool name	LUCI (Land Utilisation and Capability Indicator) formerly Polyscape	References
Impacts assessed	Water quality (nitrogen, phosphorous and sediment run-off) flood risk, carbon sequestration, habitat connectivity.	
Sectors covered	Mountains, moors and heaths; Semi-natural grasslands; Enclosed farmland; Woodland; Freshwater, wetlands and floodplains; Urban	
Geographical scope	Site to catchment or landscape scale.	
Modelling approach	LUCI is GIS-based spatially explicit ecosystem service model. It is a process-based tool which maps ecosystem services using a range of algorithms that maintain biophysical principles and spatial connections using lookup tables, combined with topographic routing of water, sediment and nutrients over the landscape. It is spatially explicit at the resolution of the topographic data layer used: model applications to date have used a 5m by 5m resolution.	Jackson *et al.* 2013
Main model outputs	Agricultural productivity, carbon stock and condition, flood mitigation and concentration. Accumulation of nitrogen, phosphorous over the landscape. In stream discharge, nitrogen and phosphorous concentration and load	
Main data needs	Required spatial data layers: Digital Elevation Model topography layer, Land use (several supported, for UK LCM2007), Soil type (several supported, for UK NATMAP) If available: Long term annual average precipitation and predicted evapotranspiration, Detailed river network Lookup tables (values provided for supported datasets): Soil and biomass carbon, land use export coefficients for nitrogen and phosphorous, cost distance for species dispersal, soil fertility, drainage and waterlogging	
Main limitations	Does not report uncertainty. Does not include valuation.	
Validation/ robustness	Quantitative. Provides spatially explicit ecosystem service trade off maps.	
Scottish/UK case study examples	Welsh Government Glastir Monitoring and Evaluation Programme (GMEP). Loweswater catchment modelling for Defra. Natural England Bassenthwaite catchment project.	Emmett *et al.* 2014 Norton *et al.* 2014
Examples of integrated use	In the GMEP project LUCI has been integrated with the Multimove habitat and species model and with ADAS Wales Diffuse Pollution Emission Modelling Framework.	

A2.2.3 Farmscoper

Table 38 Model description: Farmscoper

Model/tool name	Farmscoper	References
Impacts assessed	NH_3, nitrate, phosphorus, pesticides, N_2O, CH_4 and CO_2	Anthony and Gooday 2010
Sectors covered	Agriculture	
Geographical scope	Farm scale, England and Wales and had been scaled to catchment level	Zhang *et al.* 2012
Modelling approach	The framework is similar to the ADAS Wales Diffuse Pollution Emission Modelling Framework, and combines a suite of models to calculate emissions of NH_3, nitrate, phosphorus, sediment, N_2O, CH_4 and CO_2. Farms can be models based on Robust Farm Type within soil and climate zones. Emissions of pesticides are calculated using the MACRO and model. Phosphorus are calculated using the PSYCHIC model. Nitrate losses are calculated using the NEAP_N, N-CYCLE, NITCAT, MANNER and EDEN models. NH_3 emissions are calculated using the NARSES and MANNER models. CH_4 and N_2O emissions are calculated using the tier one and two IPCC methodology with modifications to represent the effects of observed levels of soil compaction and poaching on N_2O emissions. Indirect N_2O emissions from leached nitrate were calculated using the appropriate nitrogen leaching model. The framework contains a meta-model of export coefficients derived from process based models describing the effects of 97 individual mitigation methods for pollutant emissions to air and water. FARMSCOPER can estimate the cost and effectiveness of mitigation methods individually, so that mitigation methods of interest can easily be identified. It also allows for the evaluation of multiple mitigation methods, as these will not simply be the sum of the impacts of the individual methods, due to interaction and competition between methods	Emmett *et al.* 2014 Anthony and Gooday 2010 Jarvis 1994 Davison *et al.* 2008 Lord & Anthony 2000, Scholefield *et al.* 1991, Lord 1992, Gooday *et al.* 2008 Webb & Misslebrook 2004, Chambers *et al.* 1999 Baggott *et al.* 2006, IPCC 2006 Anthony and Gooday 2010
Main model outputs	Emissions of NH_3, nitrate, phosphorus, pesticides, N_2O, CH_4 and CO_2. Optimisation of combined MOs.	Anthony and Gooday 2010
Main data needs	Spatial database of agricultural activity, separated by farm system type. Data on agricultural practices (stocking levels, crop rotations, fertiliser application rates, manure management) and uptake of the mitigation measure e.g June Agricultural Census, British Survey of Fertiliser Practice and Farm Practice Survey. Monthly average rainfall, temperatures and number of rain days on a 5 by 5 km^2 grid. Soil particle size distribution (percentage sand, silt and clay), organic matter content, bulk density and HOST	Anthony and Gooday 2010

Model/tool name	Farmscoper	References
	class of the dominant soil series Digital Elevation Model. Land cover data.	
Main limitations	Has currently only been developed for England and Wales, although parameterisation may be similar for Scotland.	
Validation/ robustness	Gives a consistent framework for using several existing well established models.	
Scottish/UK case study examples	Farmscoper was developed and used to model the benefits of MOs at a farm scale in Defra project WQ0106. It has been upscaled for use at a catchment scale in the Hampshire Avon Demonstration Test Catchment, and have a modified version of Farmscoper forms the basis of the ADAS Wales Diffuse Pollution Emission Modelling Framework	Anthony and Gooday 2010 Zhang *et al.* 2012 Emmett *et al.* 2014
Examples of integrated use	This tool is itself an integrated suite of models	Anthony and Gooday 2010

A2.2.4 NIRAMS

Table 39 Model description: NIRAMS

Model/tool name	NIRAMS (Nitrogen Risk Assessment Model for Scotland)	References
Impacts assessed	Nitrogen leaching	Dunn et al. 2004a, 2004b
Sectors covered	Agriculture	
Geographical scope	Scotland	
Modelling approach	Calculates N balances, weekly nitrogen leaching and catchment scale nitrogen transport	
Main model outputs	Streamwater nitrogen concentrations draining from agricultural land; outputs are reliable above 30 km^2 resolution	
Main data needs	Land use, soil, topographical, meteorological data	
Main limitations	Predicting long term changes; uncertainty of grassland N balances	
Validation/ robustness	Successfully reproduced weekly nitrogen flows in eight test catchments	
Scottish/UK case study examples	Nitrogen leaching and water nitrate concentration in Scotland	
Examples of integrated use		

A2.3 Models and tools for soil quality (WI8)

CARBINE is a forest carbon model which has been developed by Forest Research (the Forestry Commission's research agency) to assess the effects of forest-related activity on soil carbon stocks under UK conditions. It has been developed primarily to assess changes in mineral soils, but is being developed to improve modelling of effects on organic soils. The Windfarm Carbon Calculator has been developed specifically to assess the effects of wind turbine developments on the carbon stocks landscapes in Scotland, particularly those with high carbon soils. Although primary developed to assess the effect of large windfarm developments it could also be applied to smaller on-farm turbines schemes.

A2.3.1 CARBINE

Table 40 Model description: CARBINE

Model/tool name	**CARBINE**	**References**
Impacts assessed	C stocks of stands and forests in living and dead biomass and soil, and associated harvested wood products	
Sectors covered	Forestry	
Geographical scope	UK at stand, forest and national level	
Modelling approach	The model consists of four sub-models or ‘compartments’ which estimate carbon stocks in the forest, soil, and wood products and, additionally, the impact on the GHG balance of direct and indirect fossil fuel substitution attributable to the forestry system. The model is able to represent all of the introduced and native plantation and naturally-occurring species relevant to the UK. The forest carbon sub-model is further compartmentalised to represent fractions due to tree stems, branches, foliage, and roots. The soil carbon sub-model runs independently of the forest sub-model. Initial soil carbon is estimated based on land use/cover and soil texture (sand, loam, clay and peat). The timecourse of any soil carbon stock change is assumed to follow an exponential form with the magnitude of the stock change and rate constant dependent on the soil type and on the particular land-use transformation.	Robertson *et al.* 2003
Main model outputs	C stocks of stands and forests in living and dead biomass and soil, and associated harvested wood products. Impact on the GHG balance of direct and indirect fossil fuel substitution	
Main data needs	Areas and age-class distributions of each tree species. Estimates of stand structure and growth obtained from yield tables applied at the stand level. Pre-afforestation land use/cover and soil texture (sand, loam, clay and peat).	Edwards and Christie 1981
Main limitations	The impact of different forest management regimes can only be assessed for the range of tree species, yield classes and management regimes represented in published yield tables.	

Model/tool name	CARBINE	References
	The standard thinning regime assumed for most species is based on recommended practice. However, actual forest management departs significantly from these recommendations. Unmanaged or 'semi-natural' forest is poorly modelled as it is assumed to follow the same growth patterns as unthinned productive forest up to the maximum potential carbon stock. Uncertainty of modelling change in soil carbon stocks for forests on organic soils is high, although an improved version of CARBINE is being developed which incorporates elements of the ECOSSE soil model to address this.	
Validation/ robustness	Although widely used by Forest Research the model has not been subject to peer view. However, the results have been validated against available field data. The soil sub-model is based on the established Roth-C model.	Coleman *et al.* 1997
Scottish/UK case study examples	CARBINE is used by Forest Research to model carbon stocks of UK forests, and is used to generate estimates of change in forest carbon stocks for the UK LULUCF inventory.	Thompson and Matthews 1989, Mason and Kerr 2004, Broadmeadow and Matthews 2003, Brown *et al.* 2016a
Examples of integrated use	An improved version of CARBINE is being developed which incorporates elements of the ECOSSE soil model to improve modelling of change in soil carbon stocks for afforested organic soils.	

A2.3.2 SPACSYS

Table 41 Model description: SPACSYS

Model/tool name	SPACSYS	References
Impacts assessed	Predicts crop yield, carbon sequestration, nitrate leaching loss, and emissions of carbon and nitrogen gases in agroecosystems.	Wu *et al.* 2007
Sectors covered	Agriculture	
Geographical scope	Site	
Modelling approach	The model describes crop yield, nitrate and carbon cycling, and it includes a soil water component that includes representation of water flow to field drains as well as downwards through the soil layers. The model is process based for the crop and the soil components. The model can also be run in a 3D-root mode at the single plant level to assess the effects of root growth on the uptake of nitrogen. The root growth, direction and elongation rates are modelled.	Wu *et al.* 2007
Main model outputs	Simulated results including daily and annual crop biomass, carbon and nitrogen pools/fluxes, water budget and daily fluxes of NH_3, CH_4, N_2O, nitric oxide, and dinitrogen.	Wu *et al.* 2015

Model/tool name	SPACSYS	References
Main data needs	Crop management, Soil parameters include texture, bulk density, pH etc., and daily climate data (max & min temperature, precipitation, wind speed and either vapour pressure or relative humidity, and either global and net radiation or cloudiness and sunshine hours).	
Main limitations	Required inputs, and the sparse level of validation, particularly for cropping systems in the UK.	
Validation/ robustness	The model has been validated for N_2O emissions for grassland and arable systems in the UK and Italy. At the China sites the model was validated for soil carbon and N_2O emissions. The 3D root model has been validated against white clover, winter wheat.	Wu *et al.* 2015, Abalos *et al.* 2016 Perego *et al.* 2016 Zhang *et al.* 2016a & 2016b Bingham & Wu 2011
Scottish/UK case study examples	The model has been validated against N_2O emissions from a manuring trial conducted in Edinburgh. The model has also been validated against grassland for the south-west of England.	Wu *et al.* 2015 Abalos *et al.* 2016
Examples of integrated use	No information	

A2.3.3 Windfarm carbon calculator

Table 42 Model description: Windfarm carbon calculator

Model/tool name	Windfarm carbon calculator	References
Impacts assessed	The Windfarm carbon calculator is the Scottish Government's tool to support the process of determining wind farm developments in Scotland. The tool assesses, in a comprehensive and consistent way, the carbon impact of wind farm developments.	
Sectors covered	Windfarms	
Geographical scope	Scotland on a site by site basis	
Modelling approach	The latest version of the carbon calculator is a web-based application linked to central database, which stores all of the data entered. Emissions due to construction and operation of the windfarm area estimated from life cycle analysis. Peat which is removed is assumed to be instantaneously oxidized. The carbon dynamics of disturbed peat on site are modelled using IPCC Tier 1 methodology as default, although more complex modelling can be accommodated where available. Change in the carbon stocks of forests can be modelled using either a simple methodology based on yield classes or more detailed modelling based on the 3PG tree growth model.	Scottish Government Nayak *et al.* 2008, Nayak *et al.* 2010, Smith *et al.* 2011 Xenakis *et al.* 2008
Main model outputs	Loss of carbon due to production, transportation, erection, operation and decommissioning of wind farm and back up generation provision; change in carbon dynamics of peatlands; changes in carbon stocks due to	

Model/tool name	Windfarm carbon calculator	References
	forestry clearance; impacts of forestry management on windfarm carbon emission savings	
Main data needs	Emission factor for displaced power source, site capacity factor, and rated capacity of turbines. Life cycle analysis data for carbon losses due to production, transportation, erection, operation and decommissioning of wind farm. Areas of peat affected removed and affected by drainage. Peat depth. Data on the extent and type of structures on site and extent of restoration of drained peat. Area and average carbon stock of forest felled. Average temperature.	
Main limitations	IPCC emission factors are used for emissions from drained peatlands. These may not be appropriate for UK peatlands, particularly blanket bogs. Model is site specific.	
Validation/ robustness	Model has been peer reviewed	Nayak *et al.* 2010
Scottish/UK case study examples	Model and previous versions of it is the standard tool for assessing the carbon balance of Scottish Windfarms.	
Examples of integrated use	No information	

A2.4 Models and tools for flood management and water use (WI9)

The models selected were chosen because they are best able include the effects of some or all of the land cover and soil factors which are likely to be affected by the MOs and have consequences for flood risk and water use.

A2.4.1 IHMS

Table 43 Model description: IHMS

Model/tool name	IHMS	References
Impacts assessed	Changes in water resources (surface and groundwater) availability due to land use and climate changes	Ragab and Bromley 2010, Ragab *et al.* 2010
Sectors covered	Water resources, Hydrology and Agriculture	
Geographical scope	Catchment scale	
Modelling approach	Distributed – Physically based hydrological process-daily based.	
Main model outputs	All water balance components, evaporation, infiltration, stream flow, groundwater recharge, runoff, plant water uptake, groundwater levels, soil moisture, wetness	Ragab and Bromley 2010

Model/tool name	IHMS	References
	index,	
Main data needs	Rainfall, climate, soils, land cover, elevation, vegetation/ land cover parameters, stream parameters	Ragab and Bromley 2010
Main limitations	Not for national scale (i.e. UK as a whole), best for catchment scale.	
Validation/ robustness	Has been validated for several catchment without problems.	D'Agostino *et al.* 2010; Montenegro and Ragab 2010, 2012
Scottish/UK case study examples	Currently is successfully used for Eden Catchment, Scotland and 5 other catchment across the UK; Pang, Don, Frome, Fowey and Ebbw.	DRY project-NERC grant (2014-2018): http://www1.uwe.ac.uk/et/research/dry/dryprojectsummary.aspx
Examples of integrated use	Linked to MODFLOW (groundwater flow model)and SWI (Seawater intrusion model) models	Ragab *et al.* 2010

A2.4.2 SALTMED

Table 44 Model description: SALTMED

Model/tool name	SALTMED	References
Impacts assessed	Changes in water balance components, crop growth, yield and nitrogen cycle due to changes in land use, water availability, field, Nitrogen fertilizers, and climate changes (e.g. CO_2, temperature, drought etc.)	Ragab 2015a
Sectors covered	Agriculture	
Geographical scope	Field scale	
Modelling approach	Field scale model, physically-biologically based process-daily based	Ragab 2015a
Main model outputs	All water balance components, evaporation, infiltration, irrigation, drainage, biomass, dry matter, yield, plant water uptake, soil moisture, soil salinity, soil nitrogen, etc.	Ragab 2015a
Main data needs	Rainfall, climate, soils, land cover, vegetation (crops/trees) parameters, land management parameters, nitrogen-fertilizers (organic, inorganic) input, .yjv	
Main limitations	Field scale only	
Validation/ robustness	Has been validated for several fields worldwide without problems	Ragab *et al.* 2015b, Pulvento *et al.* 2015 (There are at least 20 papers on validation of SALTMED)
Scottish/UK case study examples	Currently is in use at Harper Adams University, UK	See more at Water4Crops EU funded project web site at: http://www.water4

Model/tool name	SALTMED	References
		crops.org/
Examples of integrated use	Will be integrated into a catchment scale model as part of the DRY project	DRY project- NERC grant (2014-2018): http://www1.uwe.ac.uk/et/research/dry/dryprojectsummary.aspx

A2.5 Models and tools for land use and land cover (WI10)

Changes in land use and land cover are likely to be driven by a number of other factors as well as climate change mitigation measures, and the effect of these measures may be small compared to other demands on land such as the need to provide timber, food, housing and recreational opportunities and may also change in response to climate change and market and policy forces. It is therefore difficult to separate out the effects of MOs on land use and land cover from wider effects. The LULUCF inventory contains information on land use and land cover for each UK administration, and is able to protect change in land use and management and consequent change in GHG emissions and soil carbon stocks. The LULUCF inventory is able to produce projections of the effect of land use and management on GHG emissions and carbon stocks to 2050 using scenarios which can be developed based on policy aspirations or projected market trends.

To assess the land use effects of larger scale changes caused by afforestation policy or a change in demand for livestock products, land allocation models, like spatial econometric models, can be used.

A2.5.1 LULUCF Inventory

Table 45 Model description: LULUCF Inventory

Model/tool name	LULUCF Inventory	References
Impacts assessed	GHG emissions and removals and change in carbon stocks in living biomass, soil, dead organic matter and harvested wood products as a result of change in land use and management.	Brown *et al.* 2016a
Sectors covered	Grassland, Cropland, Forest, Wetland, Settlement Land, Other Land	
Geographical scope	UK administrations, Jersey, Guernsey, the Isle of Man and the Falkland Islands. Can be disaggregated to local authority level.	
Modelling approach	The LULUCF inventory uses methodology laid out by the Intergovernmental Panel on Climate Change (IPCC).	IPCC 2006, IPCC 2013

Model/tool name	LULUCF Inventory	References
	Much of the UK LULUCF inventory uses a simple "Tier 1" approach in which a default emission factor (EF) for an activity is multiplied by "activity data" such as the area of land undergoing a particular activity or the quantity of material involved. For more significant activities more complex methodologies are used e.g the CARBINE model is used to generate estimates of change in carbon stocks in Forests, an exponential model is used to assess change in soil carbon stocks, and UK specific emission factors are being developed for peatland drainage and rewetting. The UK LULUCF inventory is compiled by aggregating inventories for the constituent administrations. Emissions and removals can be disaggregated to a statistical basis to be mapped at Local Authority level. The LULUCF inventory is able to produce projections of the effect of land use and management on GHG emissions and carbon stocks to 2050 using scenarios which can be developed based on policy aspirations or projected market trends.	
Main model outputs	GHG emissions and removals; change in carbon stocks in living biomass, soil, dead organic matter and harvested wood products.	
Main data needs	Data on land use and management, including the extent of farming practices, peat extract activity, and wildfires. To produce projections to 2050 scenarios for change in land use and management are needed.	
Main limitations	In its current form the LULUCF inventory is does not use spatially explicit activity data, and so apportions activity to soil type and climate on a statistical (proportional) basis. However a methodology is being developed which will allow the LULUCF inventory to assimilate spatially explicit land use data and track "land use change vectors" for particular land parcels. In some cases the IPCC default Tier 1 EF may not fully reflect UK conditions. For example the IPCC Tier 1 EFs for Wetland Drainage and Rewetting (WDR) are more relevant to fens and raised bogs than to the blanket bogs prevalent in much of Scotland. A DBEIS (formerly DECC) funded research project which is due to report in autumn 2016 is compiling improved EFs and activity data for WDR activities in the UK.	
Validation/ robustness	The LULUCF inventory is compiled using internationally agreed methodology, and the annual inventories are subject to international review.	
Scottish/UK case study examples	Used to produce annual GHG inventories for the LULUCF sector for the UK and its constituent administrations.	Brown *et al.* 2016a, Salisbury *et al.* 2016
Examples of integrated use	Uses the CARBINE forest carbon model to assess change in forest carbon stocks.	

A2.5.2 Spatial econometric models

Table 46 Model description: Spatial econometric models

Model/tool name	Spatial econometric models	References
Impacts assessed	Agricultural land use and production, impacts of market and policy changes (e.g. prices, subsidies) and impacts of changes in biophysical constraints	Fezzi and Bateman 2011
Sectors covered	Agriculture	
Geographical scope	England and Wales, 5x5 km	
Modelling approach	Spatially disaggregated, structural econometric model of agricultural land use and production	
Main model outputs	Land use shares in each grid square, crop and livestock production	
Main data needs	Historic spatial data on land use, livestock and crop production, prices Data for future scenarios (e.g. prices)	
Main limitations	Does not exist for Scotland (though being developed by a PhD student in SRUC)	
Validation/ robustness	No information	
Scottish/UK case study examples	Climate change impacts on food production	Fezzi *et al.* 2015
Examples of integrated use	No information	

A2.5.3 Agent based land use models

Table 47 Model description: Agent based land use models

Model/tool name	Agent based land use models	References
Impacts assessed	Agricultural land use and production, impacts of market and policy changes (e.g. prices, subsidies) and impacts of changes in biophysical constraints	Murray-Rust *et al.* 2014a, 2014b
Sectors covered	Rural land use	
Geographical scope	Europe/UK	
Modelling approach	Empirical agent-based model	
Main model outputs	Depends on the model, an example: economic (gross margin difference), environmental (land use cover, nitrogen use, diversity) and social (access to green space) outputs	Guillem *et al.* 2015
Main data needs	Spatial land use data, climatic and soil data, data on farmers' behaviour	
Main limitations	Difficult to validate, mostly only calibration happens	Brown *et al.* 2016b
Validation/ robustness	See above	
Scottish/UK case study examples	Land use and ecosystem services in a Scottish arable catchment Energy crop production in the UK	Guillem *et al.* 2015

Model/tool name	Agent based land use models	References
		Alexander *et al.* 2013
Examples of integrated use	Skylark population model	Guillem *et al.* 2015

A2.6 Models and tools for biodiversity (WI11)

The selection of models and tools for the assessment of biodiversity impacts focussed on those determining direct effects on terrestrial biodiversity. Collectively these models cover a range of indicators recommended by the European BioBio project (Herzog *et al.* 2012) including those relating to *Habitat Diversity* and *Species Diversity* of key groups (i.e. spiders, vascular plants and bees). Models/Tools for assessing biodiversity impacts are primarily related to habitat type with some tools (i.e. AgBioscape and SRUC's Biodiversity Calculator) also having the potential to model different land management options (e.g. crop rotations in the case of AgBioscape). Consequently the models outlined below are typically effective for detecting impacts of MOs that result in changes to landcover (i.e. Agroforestry, Afforestation, Peatland restoration, Reduced livestock product consumption and Incorporating legumes in grass mixes and crop rotations). Models/tools are less sensitive in detecting impacts of MOs that influence habitat quality or that involve finer changes to land management (e.g. Increased uptake of precision farming techniques, Achieving and maintaining optimal soil pH level and Optimising mineral nitrogen fertilisation).

A2.6.1 Interactive Habitat Network User Tool

Table 48 Model description: Interactive Habitat Network User Tool

Model/tool name	Interactive Habitat Network User Tool	References
Impacts assessed	The interactive online tool assesses the impact of land use change (e.g. afforestation/peatland restoration) on structural and functional ecological connectivity for four key habitats (i.e. Broadleaved woodland, Heathland, Neutral grassland and Wetland). For those wishing to create additional networks (e.g. for a specific species) or utilise the system in GIS additional information is available from SNH Natural Spaces website and/or Phil Baarda, SNH. These include: Spatial datasets- habitat networks indicated above, acid grassland network, hotspots for habitat creation (i.e. for Broadleaved woodland, Wetland and, Neutral grassland). Users manual-Outlines modelling procedure using GIS	http://www.snh.gov.uk/land-and-sea/managing-the-land/spatial-ecology/habitat-networks-and-csgn/interactive-habitat-network-tool/ http://gateway.snh.gov.uk/natural-spaces/index.jsp Blake & Mattisson

Model/tool name	Interactive Habitat Network User Tool	References
	ArcMap including spatial data requirements (Blake & Mattisson 2012). Tools: ArcMap GIS tool to help automate the creation of new networks.	2012
Sectors covered	Agriculture, Forestry, Peatlands	
Geographical scope	Central Scotland Green Network area, Loch Lomond and the Trossachs national park and the Scottish Borders	
Modelling approach	GIS based model utilising least-cost modelling procedures based on Forest Research landscape ecology model BEETLE (Biological and Environmental Evaluation Tools for Landscape Ecology).	http://www.snh.gov.uk/docs/B692517.pdf, Watts *et al.* 2010
Main model outputs	A series of spatial maps illustrating extent of existing habitat networks. Interactive online tool enables altering current land use (e.g. creation of a new woodland of a specific size in a specific location) and determining the impact of this change on the extent of existing networks. Summary information on network metrics (i.e. the number of networks and the size of each network) are provided.	
Main data needs	Scenarios are inputted by manually drawing the area of proposed land use change and proposed new habitat on the online GIS system. New habitat networks are then generated to determine the impact. New habitat networks can be calculated for species with either high or moderate dispersal.	
Main limitations	Online tool restricted with respect to the habitats and geographical locations noted above. Networks are not based on actual species but Generic Focal Species for the habitat in question. This generic species is given either moderate or low dispersal powers. Decisions for land-use change should not solely be based on habitat network modelling and additional factors should be taken into account. For example, creation of native woodland on a SSSI raised bog may increase the extent of a Broadleaved woodland but would result in the loss of a valuable habitat.	
Validation/ robustness	Models based on spatial datasets that categorise habitats at a specific point in time. Potential errors with respect to incorrect categorisation of habitats and changes to land cover. Differences in habitat quality are not acknowledged during network creation. Little scientific evidence investigating the impact of functional/structural connectivity on actual species dispersal.	
Scottish/UK case study examples	Habitat network modelling has been used to explore the extent of current habitat networks in Falkirk, Ayrshire and Glasgow to prioritise areas habitat creation to optimise ecological connectivity. Outputs from this tool are of direct relevance to the BioBio Indicator Habitat Diversity	Chetcuti *et al.*, 2011 Moseley *et al.* 2008, Smith *et al.* 2008 http:/www.forestry.gov.uk/fr/ infd-

Model/tool name	Interactive Habitat Network User Tool	References
		6w7evk Herzog *et al.* 2012
Examples of integrated use	Potential integration with other spatial datasets available for Scotland including: suitability mapping for native woodland creation, carbon stock mapping, changes to distribution of 'prime' land under climate change and Ecosystem Service Mapping.	Lilly & Baggaley 2013, Towers *et al.* 2011, Brown *et al.* 2008, Winn *et al.* 2015a

A2.6.2 SRUC's Biodiversity Calculator

Table 49 Model description: SRUC's Biodiversity Calculator

Model/tool name	SRUC's Biodiversity Calculator	References
Impacts assessed	The calculator assesses the impact of land use change (e.g. from winter wheat to unimproved pasture) on the number of vascular plant and spider species in a field.	Yelloy 1999
Sectors covered	Agriculture, Peatlands	
Geographical scope	Scotland	
Modelling approach	Biodiversity data were collected from agricultural land covers across Scotland. From these data predictive models were generated from Generalised Linear Interactive Modelling using linear regression to determine the importance of measured environmental variables (e.g. altitude, land use) on response variables (i.e. the number of vascular plant and spider species). Resultant models predict the richness of plant and spider assemblages in a field based on specific input parameters (e.g. current land cover, proposed new land cover, altitude, stocking density).	Murphy *et al.* 1998
Main model outputs	Interactive tool provides graphical and textual information on the predicted number of vascular plant and spider species in the current land use and in the proposed new land use, alongside the mean value for a field of the type in question.	
Main data needs	The interactive tool requires manual inputting via text/drop down menus of the follow information: Field altitude and area, current and proposed land use, years since sown, stocking density, uncultivated headland width, number of cuts, presence of hedgerows and vegetation type.	
Main limitations	The model is restricted to the following land covers: spring barley, improved pasture, set-aside, winter wheat, oilseed rape, spring barley, heather moorland, gorse grassland, unimproved pasture, root crops. The model is restricted to spiders and vascular plants. Model simply reports the number of species and provides no information on which species are present and their rarity/ conservation status. Interactive tool restricts environmental variables to those that the user can easily determine. Environmental variables included in the initial linear regression models	

Model/tool name	SRUC's Biodiversity Calculator	References
	that are not readily measured (e.g. soil organic content) are omitted to facilitate use by target audience (e.g. farmer/agricultural advisor). The tool calculates the impact of land use change at a field level and the importance of landscape heterogeneity at promoting biodiversity is thus not taken into account.	
Validation/ robustness	The original models (i.e. inclusive of environmental variables that are not readily measured) were found to be accurate +/- 4 species for vascular plants and 68% accurate for spiders. Removal of environmental variables that are difficult to determine from the interactive tool will decrease prediction accuracy. Original modelling determined different optimum models for different field types. The interactive tool draws results from a single model for each response variable and thus robustness of predictions are reduced. Prior to tool creation a prototype determined functionality of interface and outputs on the proposed interface for non-experts and target users. This determined that the interface was easy to navigate and outputs easy to interpret. The final online tool was tested by a novice user, by an expert and the author.	Downie *et al.* 1999, Wilson *et al.* 2003
Scottish/UK case study examples	The interactive tool was based on data collected from across Scotland encompassing the main agricultural land uses in Scotland. Predictive models were generated from these data and the accuracy of these models tested. Impact of changes to management practices (e.g. reduction in grazing intensity, creation of water margins) on spider and vascular plant richness. This information was combined with expert opinion to determine the impact of implementing management practices to promote biodiversity. Tool outputs are of direct relevance to the BioBio Species Diversity Indicators Vascular Plants and Spiders	Downie *et al.* 1999, Wilson *et al.* 2003, McCracken 2000 McCracken 2000 Herzog *et al.* 2012
Examples of integrated use	The biodiversity calculator has the potential to generate metrics for use in cost-benefit analyses (e.g. to explore the synergies and trade-offs when implementing different adaptation or agri-environment options).	

A2.6.3 Eco-Serve GIS

Model/tool name	Eco-Serve GIS	References
Impacts assessed	GIS based Toolkit that generates spatial maps for nine ecosystem services (i.e. Accessible Nature, Carbon Storage, Local Climate Regulation, Water Purification, Air purification, Noise regulation, Education, Green travel and Pollination). Maps illustrate both requirement for each service (i.e. human demand) and capacity to deliver that	Winn *et al.* 2015a

Model/tool name	Eco-Serve GIS	References
	service. Multi-functionality of delivery across ecosystem services are also assessed.	
Sectors covered	Agriculture, Forestry, Peatlands	
Geographical scope	England, Scotland and Wales	
Modelling approach	EcoServ-GIS uses simplified and generalised models of the relationships between landscape variables and ecosystem services. Ecosystem Service Capacity is determined by identifying habitats/ecosystems that provide a particular service and giving these a grade based on their capacity to provide that service. Demand for each service is also graded based on both the number of beneficiaries and the potential benefits derived. Both demand and capacity grades range from low to high (1 to 100) and are relative to the study area in question. The multi-functionality toolbox creates a multi-functionality score based on the proportion of services that are met.	
Main model outputs	The toolkit creates a series of ecosystem service maps (including both requirement and delivery), multi-functionality maps, habitat maps, ecological connectivity maps and Biodiversity Opportunity Areas. The resulting maps are visually interpreted to determine where ecosystem services occur, and indicating where there is relatively high demand for a service, or high capacity to deliver a service. This tool is designed for simultaneously comparing several ecosystem services. The following metrics are calculated: mean capacity, mean demand, mean GI assets capacity, multi-functionality score, priority multi-functionality score, number of Ecosystem Service Benefiting Areas, and number of Management Zones.	
Main data needs	OS MasterMap data. Potential to incorporate a range of other datasets (e.g. Digital Terrain Models, Core paths, Native Woodland Scotland Survey). Incorporation of additional spatial datasets will increase the number of ecosystem services that can be mapped. Software requirements: ArcGIS Desktop (version 10.2.2), an Advanced level license with the Spatial Analyst extension.	
Main limitations	Ecosystem services mapped are restricted to the nine services outlined above. Mapping output is influenced by the underlying accuracy and resolution of the input spatial datasets. Many of the ecosystem services relate to populated areas and the toolkit is therefore less applicable to remote/non-urban areas (e.g. upland landscapes). The resultant ecosystem service maps do not attempt to quantify the actual level of service delivery/demand but instead provides a relative measure for the target area. It is therefore not applicable to compare maps from different target areas. Information is largely not incorporated on habitat, or	

Model/tool name	Eco-Serve GIS	References
	ecosystem quality. Outputs are based on relatively simple models and capacity and demand only provide a proxy for service provisioning. Limitations are dependent on the ecosystem service in question. Winn *et al.* (2015a) suggest that alterative tools such as InVEST are more suitable. InVEST has not been as extensively tested in the UK. Interpretation of maps for use in decision making requires expert opinion and should consider other information.	Winn *et al.* 2015a
Validation/ robustness	The toolkit was developed in Durham, NE England and subsequently tested in the South Downs National Park and NIA, the Nene Valley NIA (Northamptonshire) and within Somerset. Reliability of service maps range from Low in the case of Pollination to High in the case of Education and Accessible nature.	Winn *et al.* 2015a
Scottish/UK case study examples	The EcoServ-GIS toolkit was used to evaluate the multiple benefits derived from green networks in the Cumbernauld Living Landscape project. Identifying the most valuable green networks with respect to the delivery of multiple ecosystem services and helping to define management priorities for each area. Outputs from this toolkit are relevant to the BioBio Species Diversity Indicator Bees and Habitat Diversity	Winn *et al.* 2015b Herzog *et al.* 2012
Examples of integrated use	Potential to incorporate output ecosystem service maps with other spatial datasets such as suitability mapping for native woodland creation and changes to distribution of 'prime' land under climate change. The digital habitat map produced from the Eco-Serve GIS can be used to produce automated ecological network maps (e.g. thus potential integration with SNH's integrated habitat network modelling tools) and to map biodiversity opportunity areas.	Towers & Sing 2012, Brown *et al.* 2008

A2.6.4 AgBioscape

Table 50 Model description: AgBioscape

Model/tool name	AgBioscape	References
Impacts assessed	AgBioscape is a GIS based modelling system that simulates interactions between a range of target focal species (e.g. crop pests, natural predators and farmland birds), crop, management and landscape characteristics. Model simulations explore the impact of pre-determined cropping, field and landscape modifications on, for example, pest and natural predator populations across time. This can help to determine optimum modifications (e.g. those resulting in the lowest pest or highest predator densities).	Begg 2013, http://www.pure-ipm.eu/
Sectors covered	Agriculture	

Model/tool name	AgBioscape	References
Geographical scope	Simulated landscapes.	
Modelling approach	Discrete time population models (e.g. pest population dynamics) are combined with spatially explicit simulated agricultural landscapes. A matrix population modelling approach is used to spatially simulate the population dynamics of local populations over time. A series of land use/management scenarios are assigned to a simulated agricultural landscape to enable the user to alter landscape metrics (e.g. area and location of hedgerows) and to specify temporal changes in landscape structure (e.g. cropping patterns).The population matrix and simulated agricultural landscapes are overlaid. Transition matrices are used to specify demographical changes in life cycle stages that occur over time as a function of interactions (both within and between species), habitat, landscape and environmental conditions.	
Main model outputs	Model produces a series of spatially explicit simulated populations (e.g. pest population density) over time based on the specific scenarios inputted (e.g. different crop rotations). Metrics can be obtained from these scenarios (e.g. annual aphid population densities over a 100 year period) to compare scenarios.	
Main data needs	Modelling requires information on target species ecology (e.g. specificity of pest species, dispersal, life-history information, habitat specific survival rates).	
Main limitations	Outputs of models are dependent on the availability and reliability of ecological data on target species. Accuracy of ecological inputs will impact model predictability. Modelling does not take into account impact of habitat quality on target species ecology (e.g. survival rate). Model currently is based on simulated landscapes. Model is currently not openly available.	
Validation/ robustness	AgBioscape model outputs are largely consistent with empirical findings highlighting the influence of landscape composition and crop management on crop-pest systems. Modelling has, however, only been conducted on simulated landscapes without ground truthing on actual landscapes.	Begg 2013
Scottish/UK case study examples	AgBioscape was used to compare different rotational control strategies for the maize pest *Diabrotica virgifera virgifera.* Simulated models were used to evaluate strategies for control of cereal aphids by parasitic wasps. AgBioscape was also used to explore the impact of agri-environment prescriptions on populations of farmland birds, crop pests and natural predators over a 350 year period. Outputs from this toolkit are relevant to the BioBio Species Diversity Indicator Bees and Habitat Diversity.	Begg 2013 Begg & Dye 2015 Herzog *et al.* 2012
Examples of integrated use	Development of the AgBioscape modelling approach could assist in the development of a decision support tool for land-managers/ policy makers/agricultural	

Model/tool name	AgBioscape	References
	advisors. This tool could explore different scenarios with respect to the placement and nature of agri-environment schemes/compulsory greening measures and to spatially determine optimum configurations for pest regulation and/or biodiversity.	

A2.7 Models and tools for animal health and animal welfare (WI12)

Animal health and/or animal welfare are likely to be affected by many MOs. The animal health modelling literature is substantial, usually specific for certain diseases, livestock species and management/treatment. No models or tools were found for assessing the general health or welfare impacts.

A2.8 Models and tools for crop health (WI13)

Precision farming (MO2) and Optimal soil pH (MO3): In principle, the measures that affect the productivity of the crop and therefore may have an impact on the crop health can be assessed with dynamic deterministic models of crop growth combined models of the soil carbon, nitrogen and water cycle. The measures identified include optimizing pH, and precision farming which are operating by increasing the nutrient supply to the crop. In general, the models have not been validated against data from crops receiving low levels of fertilizer nitrogen, and therefore there is a tendency for the yield predictions to be less reliable.

MO6 Incorporating legumes in grass mixes/ crop rotations: Many of the dynamic and deterministic crop models (e.g. APSIM, DSSAT etc.) can be used to model crop rotations, and do simulate the sequence effects where one crop influences the environment under which the following crop grows and hence affects the yield. However, these models do not consider the effects of the accumulation of soil borne diseases and weeds and thus the impact these will have on yield. The approaches that consider the break crop effect of legume on the rotation are either rule-based (Rule based rotation generator) or a combination of models which describe the effects of the sub-components (e.g. LUSO).

A2.8.1 APSIM

Table 51 Model description: APSIM

Model/tool name	APSIM	References
Impacts assessed	(1) The yield loss based on expected yield in the absence of disease and expected disease effects on leaf area duration (2) The effect of eyespot on green leaf area and the yield (eyespot model being developed)	Poole & Arnaudin 2014 Al-Azri *et al.* 2015
Sectors covered	Crop production	
Geographical scope	World wide	
Modelling approach	Dynamic deterministic model of crop and soil processes	
Main model outputs	Yield, green leaf area, leaf area duration, N_2O, leaching changes in soil carbon	https://www.apsim.info/Documentation.aspx
Main data needs	Daily weather data, soils characteristics, management of the crop, (1) expected effect on the leaf area duration, (2) data required to predict of disease development in relation to crop growth stages	Poole & Arnaudin 2014, Al-Azri *et al.* 2015
Main limitations	The model has been validated for typical management practices	
Validation/ Robustness	APSIM has been used extensively across the world to predict yields	
Scottish/UK case study examples	Development of eyespot model	Al-Azri *et al.* 2015
Examples of integrated use	Green leaf retention calculator	Poole & Arnaudin 2014

A2.8.2 DSSAT

Table 52 Model description: DSSAT

Model/tool name	DSSAT	References
Impacts assessed	The effect of disease on the crop is a required input to the model. Therefore the model assesses the effect on yield from a level of disease severity.	http://abe.ufl.edu/jjones/ABE_5646/Week%207/Pest%20Module%20from%20DSSAT4%20Volume%204.pdf
Sectors covered	Crop production	
Geographical scope	World wide	
Modelling approach	Dynamic deterministic model of crop and soil processes	
Main model outputs	Yield, green leaf, N_2O, leaching changes in soil carbon	http://dssat.net/
Main data needs	Daily weather data, soils characteristics, management of the crop, impact of the disease on the green leaf area	http://dssat.net/ http://abe.ufl.edu/jjones/ABE_5646/

Model/tool name	DSSAT	References
		Week%207/Pest%20Module%20from%20DSSAT4%20Volume%204.pdf
Main limitations	The model has been validated for typical management practices	
Validation/ robustness	DSSAT and the family of crop models embedded in the framework have been used extensively across the world to predict yields, soil carbon & nitrogen flows	http://dssat.net/
Scottish/UK case study examples	Used to predict potato yield under climate change	Daccache *et al.* 2011a & 2011b
Examples of integrated use	No information	

A2.8.3 LUSO

Table 53 Model description: LUSO

Model/tool name	LUSO (The Land Use Sequence Optimiser)	References
Impacts assessed	Optimizes the crop rotation, based on any expected seasonal and price situation. The model describes the effects of weeds and diseases on the crop rotation. It also describes the nitrogen contribution the legume makes to the following crop as a fertilizer equivalent.	Lawes & Renton 2010
Sectors covered	Crop rotations that include cereals and legumes	
Geographical scope	Developed for Australian farming conditions	
Modelling approach	Nitrogen – rule based Weeds – based on the RIM model that describes seedbank dynamics.	
Main model outputs	The effect of the nitrogen cost, weeds and diseases on the profitability of the cropping sequence.	
Main data needs	Length of the sequence, details on the weed seedbank, and the weed population dynamics, nitrogen costs, soil nitrogen status, soil disease population and details on the costs.	
Main limitations	Developed for Australian systems, and would need UK specific data (like nitrogen application to crops, weed prevalence and disease burden).	
Validation/ robustness	No information	
Scottish/UK case study examples	No information	
Examples of integrated use	No information	

A2.8.4 ROTOR

Table 54 Model description: ROTOR

Model/tool name	ROTOR (Rule based rotation generator)	References
Impacts assessed	Evaluates a range of feasible rotations on gross margins, leaching losses, fertilizer requirements and N_2O emissions.	Reckling *et al.* 2016a, 2016b
Sectors covered	Crop rotations.	
Geographical scope	EU	
Modelling approach	IPCC assessment of the leaching losses and N_2O emissions.	
Main model outputs	leaching losses, fertilizer requirements and N_2O emissions	
Main data needs	Agronomists define input variables such as crops, restriction values, and describe environmental, economic and phytosanitary indicators of the crops within the rotations.	
Main limitations	Based on expert opinion.	
Validation/ robustness	Based on the judgment of experts. At this stage the inputs may be revised and the model re-run.	
Scottish/UK case study examples	Used to assess Scottish rotations as part of the EU project Legume Futures.	
Examples of integrated use	No information	

A2.9 Models and tools for economic impacts (WI14-WI16)

In assessing both the farm and off-farm wider economic effects (both co-benefits and adverse side effects) multi-sectoral economic models of Scotland exist which can quantify all of these effects, and separately distinguish by sector and activity where relevant. In principle the models below can explore and quantify the qualitative and quantitative consequences of a host of MOs – and the details below give examples of such uses. In each case however, it is appropriate to ensure that the modelling system being used is able to reflect important aspects of the economic question being addressed in that use. For example, models of a single "Agriculture" sector – but with multiple non-agricultural activities identified - can be useful for qualitative descriptions of within and outwith agriculture effects, but are unable to capture what might be important heterogeneity within that sector; models which appropriate consider land use and competing uses would be appropriate for exploring cases where there might be alternative uses of this factor of production.

A2.9.1 CGE models

Table 55 Model description: CGE models

Model/tool name	**CGE models (e.g. AMOS)**	**References**
Impacts assessed	System-wide consequences of exogenously determined policy/non-policy options and disturbances	Harrigan *et al.* 1991
Sectors covered	All industrial sectors of economy, which could be separately identified at level of policy interest (with sufficient data and disaggregation). Current IO accounts for Scotland provide, for example, 98 sectors using Standard Industrial Classification 2007, mapping to national economic accounts.	Scottish Government 2016
Geographical scope	AMOS model framework has been applied to single region/nation analysis and inter-regional analysis. Application framework has been applied based on availability of model inputs, see below.	Jersey: Learmonth *et al.* 2007 Scotland: FAI & Macaulay & Arkleton 2003, Lecca *et al.* 2014a UK: Allan *et al.* 2007a Inter-regional UK: Gilmartin *et al.* 2013
Modelling approach	CGE model solves for equilibria in all markets for all goods and factors of production simultaneously. Comparative static or dynamic framework can show impacts in conceptual or annual time periods, and trajectory of variables between equilibria. Framework flexible to consider alternative model specifications, and so adapt to specific focus of application.	Lecca, McGregor and Swales 2013 Lecca, Swales and Turner 2009
Main model outputs	Economic variables (e.g. gross domestic product, aggregate employment, unemployment, household income) as well as sectoral levels of gross output, value-added, intermediate inputs, employment, and capital stocks. Also included are (endogenously determined) energy use (by sector), prices and costs of goods and factor inputs (including wages, return on capital). Energy use by sector is linked to CO_2 emissions, so that production-oriented measures of emissions are automatically tracked. (Consumption-oriented measures can be developed given appropriate trade-related data.)	
Main data needs	Uses IO and SAM as benchmark dataset for economic and sectoral structures, while behavioural specification and parameters appropriate for spatial scale and economy under consideration are required to configure relationships within and between markets. (These draw on new or existing econometric evidence.)	Scottish Government 2016, Emonts-Holley *et al.* 2016
Main limitations	Typically non-stochastic, calibrated to a single year's SAM and focus typically on policy simulation, not forecasting or historical analysis.	
Validation/ robustness	Tests on calibration accuracy; test simulations to check e.g. homogeneity properties of the model; extensive	

Model/tool name	CGE models (e.g. AMOS)	References
	sensitivity analysis, drawing on statistical estimates where available; outputs subject to peer review.	
Scottish/UK case study examples	Impact of onshore wind on rural and urban areas of North East Scotland Impact of expenditures related to establishing renewable energy capacity, including local content System-wide impact of energy efficiency improvements in production sectors for Scotland and UK System-wide impact of household energy efficiency improvements Energy-economy-environmental impacts on Scotland of a carbon tax – "double dividend" and the importance of revenue recycling Impact on Scotland of foot and mouth outbreak, 2001	Phimister and Roberts 2012 Gilmartin and Allan 2015; Allan *et al.* 2014a Hanley *et al.* 2006; Allan *et al.* 2007a; Anson and Turner 2009, Turner 2009 Lecca *et al.* 2014b Allan *et al.* 2014b FAI & Macaulay & Arkleton 2003
Examples of integrated use	There are examples of CGEs having been combined with energy systems models and with micro-simulation models, but these are at a very early stage of development.	

A2.9.2 IO and SAM models

Table 56 Model description: IO and SAM models

Model/tool name	IO and SAM models	References
Impacts assessed	Changes in quantities or prices and system-wide consequences	Miller and Blair 2009
Sectors covered	All sectors of economy. For example, Scottish Input-Output tables are now (August 2016) available for years 1998 to 2013, covering 98 sectors and consistent with ESA 2010 (Scottish Government, 2016). Single "Agriculture" sector covering SIC2007 sector 01, with four sectors covering forestry and fishing activities. Disaggregation of sectors possible to focus on area of policy interest and address heterogeneity within industrial sectors, while disaggregation of categories of consumption permit examination of impacts across, e.g. household income types or household characteristics.	Allan *et al.* 2007b
Geographical scope	Local, regional or national (with inter-regional/inter-national configurations possible)	
Modelling approach	Static typically, deterministic, using inter-sectoral linkages to quantify system-wide impacts of changes in individual sectors or elements of demand or inputs.	
Main model outputs	Economic variables (e.g. gross domestic product, employment, household income, the sectoral levels of output, value-added, employment and capital stocks) as well as variables linked to sectoral output, including GHG emissions.	
Main data needs	IO accounts for regions/nations of interest showing	

Model/tool name	IO and SAM models	References
	production and consumption linkages between and within sectors and elements of consumption, e.g. households, exports, etc. Non-survey approaches allow estimation of IO accounts for smaller spatial levels, although (more time-consuming) survey-based approaches can capture more refined treatment of local differences in, e.g. linkages.	
Main limitations	Assumptions in modelling using IO include passive supply curve for all factors of production (no crowding out of activity) and that sectoral production inputs are combined in fixed proportions. (So typically motivated in terms of high unemployment and unused capacity in short-run, but in regional context also by factor mobility in long-run.)	Miller and Blair 2009
Validation/ robustness	-	
Scottish/UK case study examples	Impact of community owned vs. community benefit-paying windfarm on the Shetland Islands, using SAM model for Shetland to show alternative impacts of locally-retained incomes from renewable energy project Impact of new onshore windfarm on farming households in north east Scotland Impacts of community wind power in rural areas in Scotland Disaggregation of sea fishing sector to address heterogeneity of economic linkages within fishing fleet Review of economic multipliers for Scottish agriculture Database of disaggregation of household types within SAM for Scotland 2009 IO accounts used to examine economic value of services produced by specific sectors for region/nation Impacts of changes of forestry and afforestation on Scotland and UK Uses and approach of IO/SAM modelling in context of new biofuels production, including treatment of land in such models.	Allan *et al.* 2011 Phimister and Roberts 2012 Okkonen and Lehtonen 2016 Seafish 2006 Scottish Government 2010 Ross 2016 Cambridge Econometrics 2005, 2008 McGregor and McNicholl 1992, Eiser and Roberts 2002 Allan 2015
Examples of integrated use	IO/SAM database are used as the benchmark datasets and inputs to CGE models, which is a more flexible framework for exploring the range of factor supply assumptions and production structures, of which IO/SAM are a special case. Extensions of IO/ SAMs to incorporate energy and environmental variables are common.	

A2.10 Models and tools for resource efficiency (WI17)

The energy and material recycling and resource use efficiency impacts arise from the improved utilization of nitrogen, energy and other resources on farm for the agricultural production related MOs (MO1-MO9). These changes can be captured by the models and tools developed to estimate the GHG emissions and emission intensity of livestock and crop production, like whole-farm models life cycle assessment tools and carbon calculators (e.g. AGRILCA (Williams *et al.* 2006), AgRECalc (http://www.agrecalc.com/) or CoolFarmTool (https://www.coolfarmtool.org/)). The challenge with whole-farm approaches is the derivation of national level assessment from the farm-level models. On the other hand, no national level models were found which could capture the management changes implied by the implementation of MO1-MO9.

The resource use impacts of Reduced livestock product consumption and Afforestation can be estimated via economy wide models (see Section A2.9) if they are capable of tracking biomass, energy and nitrogen flows.

A2.11 Models and tools for human health (WI18)

The reviewed GHG MOs can affect human health in various ways, from a reduction in water and air pollutants to a change in the diet and exercise level or an increase in antimicrobial resistance. Below is a list of the health impacts based on Section 3:

- NH_3 emissions: MO1, MO2, MO4, MO5, MO7, MO8
- NO_x emissions: MO1, MO4
- PM emissions: MO1, MO4, MO5, MO11
- H_2S emissions: MO8
- N leaching: MO2, MO7
- P leaching: MO2
- Release of pesticides and other chemicals to water: MO2, MO5, MO9, MO10, MO11
- Heavy metals in the soil: MO3
- Zoonosis: MO9
- Antimicrobial resistance: MO9
- Risk from handling acids: MO8

- Diet: MO10
- Exercise and mental health: MO11, MO12
- Noise: MO1

The effects of air pollution (NH_3, sulphur dioxide and PM_{10}) on human health have been explored and monetised, and they are included in the damage costs values used in the UK (Defra 2011a).

The human health impacts from nitrate pollution of watercourses and eventually drinking water consist of risk of metheamoglobinaemia and risk of cancer from nitrite-derived carcinogenic compounds. Though some estimates for these effects are available (van Grinsven *et al.* 2010), no model was found to assess this risk.

Though models exist to predict the risk of high-pesticide exposure of agricultural workers (Mage *et al.* 2000), no model was found which could assess the pesticide exposure of the general population.

As pH can affect plant-absorbable metal concentrations (e.g. lead, copper, zinc, nickel, aluminium) in soils (Section A1.3), maintaining an optimal soil pH (MO3) might decrease the risk of excessive consumption of these materials from crops. The CLEA software (Jeffries 2009) is a tool used by the Environment Agency to assess soil contamination risks; however, as it only covers home-grown produce it was not included in the assessed models. A tool suitable for assessing the risk of metal exposure as depending on soil pH for commercial agricultural land was not found. Similarly no models or tools were found for assessing the health risk arising from exposure to strong acids and H_2S (related to MO8: Low emission storage and application of organic fertiliser).

Improving animal health (MO9) might decrease zoonosis incidents but could contribute to the prevalence of antimicrobial resistance (Section A1.9). Though the literature on the various vectors' prevalence, their control mechanisms and the human health risk is wide (Lloyd-Smith *et al.* 2009), and estimates to the total aggregate human health effects and costs of selected pathogens exists for some countries (Lake *et al.* 2010, Scallane *et al.* 2015, Scharff 2012) an integrated tool linking livestock management and human illness prevalence was not found. As for the use of antimicrobials in the livestock sector and the potential effects on human health currently available data do not allow the quantification of these relationships (Rushton *et al.* 2014).

Assessing the health impacts of a change in diet (MO10) is possible and already done by comparative risk assessment models (Section A2.11.1).

Finally, the potential effects of afforestation (MO11) on human health (arising from increased exercise levels and benefits to mental health – as opposed to the air purification effects of trees) have been explored in England, deriving per ha values for woodlands (based on woodland quality and proximity to urban areas) (Bateman *et al.* 2011). Nevertheless, a tool to assess these impacts was not found.

A2.11.1 DIETRON and PRIME

Table 57 Model description: DIETRON and PRIME

Model/tool name	DIETRON and PRIME (Preventable Risk Integrated ModEl)	References
Impacts assessed	Impact of diet on cardiovascular disease and cancer mortality (the models are being expanded to include physical activity, smoking and alcohol consumption)	Scarborough *et al.* 2012b, Smed *et al.* 2016
Sectors covered	Agriculture	
Geographical scope	UK	
Modelling approach	Comparative risk assessment: association between food components and coronary heart disease, stroke, cancer derived from individual meta-analyses (sugars not included as meta-analysis were not available)	Scarborough *et al.* 2012b
Main model outputs	Mortality and costs to NHS	Scarborough *et al.* 2010
Main data needs	Baseline and alternative diet composition	
Main limitations	The correlation between health effects are not included (e.g. serum cholesterol and BMI or fruit and vegetables and dietary fibre), therefore some overestimation is possible; assumes a linear dose-response relations; a shift in an average diet is modelled (no disaggregation allows for dietary groups)	Scarborough *et al.* 2012b
Validation/ robustness	No information	
Scottish/UK case study examples	UK GHG emission based food taxes UK healthy diets	Briggs *et al.* 2013, Scarborough *et al.* 2010
Examples of integrated use	Similar comparative risk assessment models are linked a detailed agricultural modeling framework (IMPACT (the International Model for Policy Analysis of Agricultural Commodities and Trade)) and to a life cycle GHG model	Springmann *et al.* 2016a & 2016b

A2.12 Models and tools for social and cultural impacts (WI19, WI20)

Tools or models to assess the social impacts of the MOs were not found.

Cultural impacts can be classified following the ecosystem services approach, whereby cultural ecosystem services are usually grouped as aesthetic, spiritual, educational and recreational services (Millennium Ecosystem Assessment 2005). Recreational impacts are the most studies of these, particularly in relation to greenspaces. This is of relevance to the MOs Afforestation (MO11) and Peatland restoration (MO12), in some cases possibly to MO5 (Agroforestry) as well.

A2.12.1 ORVal

Table 58 Model description: ORVal

Model/tool name	**ORVal (The outdoor recreation valuation tool)**	**References**
Impacts assessed	Recreational benefits – afforestation, peatland restoration	http://leep.exeter.ac.uk/orval/
Sectors covered	Recreation sites	
Geographical scope	England	
Modeling approach	A map-based tool using a statistical model of recreational demand (person-level model aggregated to England)	Day and Smith 2016
Main model outputs	Welfare values of currently accessible and proposed greenspaces (individual site level or aggregated by regions)	
Main data needs	Map of proposed recreation sites, data on their characteristics	
Main limitations		
Validation/ robustness	No available information	
Scottish/UK case study examples	Developed for England	
Examples of integrated use		

Appendix A3. Review of the monetary values of the wider impacts

Monetary values can be derived from a number of sources including impacts on market prices, changes to costs or willingness to pay for changes to take place (e.g. improvements in environmental quality). Consequently there are differences in what these different approaches actually measure, with non-market approaches that estimate willingness to pay (e.g. contingent valuation, discrete choice experiments) able to capture total economic welfare and hence consumers' surplus. These approaches are also able to include a wider range of co-benefits in valuation scenarios (simultaneous valuation of multiple benefits may be preferred to summation of individual estimates). However, there may be concerns over the robustness of such estimates due to the often hypothetical nature of the changes being valued and the lack of a real transaction. Consequently, market price and cost based values, although arguably less complete, may be considered more defensible.

A further complication is that the direction of change being valued may be important. Implied property rights (for a given existing level of environmental quality) and loss aversion suggest that the value of lost benefits associated with a decline in environmental quality will be higher than the value of benefits gained from an improvement in quality of equal magnitude. We might also expect diminishing margin utility to be observed. For example in the context of water quality, values for changes improvements from poor to moderate or good quality may have higher values that when the change is from good to high quality, even where biological or chemical change is of similar magnitude. There may also be threshold effects, for example where a change from bad to poor status is not considered acceptable or given a lower value than a change from poor to moderate. These potential marginal values are illustrated in Figure 2.

The monetary values are presented in Table 59 with some explanation on their relevance. Further notes can be found in Sections 1.1-A3.13.

Table 59 Monetary values of the wider impacts

	Wider impact	Monetary value	Notes	Reference
WI1	Air quality: NH_3	Low central: £1,843 t^{-1} Central: £2,363 t^{-1} High central: £2,685 t^{-1}	Cost of morbidity and mortality based on willingness to pay. Recommended use for UK national evaluation; Relates to pollution from all sources and locations; 2015 prices	Defra 2015
WI2	Air quality: NO_x	Low central: £2,020 t^{-1} Central: £5,050 t^{-1} High central: £8,080 t^{-1} Values if PM is also valued: Low central: £1,683 t^{-1} Central: £4,209 t^{-1} High central: £6,734 t^{-1}	Cost of morbidity and mortality based on willingness to pay. Recommended use for UK national evaluation; Relates to pollution from agricultural sources; 2015 prices	Defra 2015
WI3	Air quality: PM	Low central: £9,103 t^{-1} Central: £11,625 t^{-1} High central: £13,211 t^{-1}	Cost of morbidity and mortality based on willingness to pay, also includes value of building soiling. Recommended use for UK national evaluation; Relates to pollution from agricultural sources; 2015 prices	Defra 2015
WI4	Air quality: other	Values for sulphur oxides : Low central: £1,581 t^{-1} Central: £1,956 t^{-1} High central: £2,224 t^{-1}	Cost of morbidity and mortality based on willingness to pay, sulphur oxides values also include materials damage. Recommended use for UK national evaluation; Relates to pollution from all sources and locations; 2015 prices	Defra 2015
WI5	Water quality: Nitrogen leaching	Lowest value: £4,278 nitrate–nitrogen t^{-1} Highest value: £17,148 nitrate–nitrogen t^{-1}	Nr damage to ecosystems (not including human health) Based on WTP for a 'healthy Baltic Sea' study (achieving 50% reduction in nitrogen load) 2008 prices Water quality monetary values highly depend on the location and the baseline pollution load - values are worked back from proposed change in eutrophication status to required change in nitrogen emissions rather than reflecting a damage cost per unit of nitrogen.	Brink *et al.* 2011
WI6	Water quality: Phosphorous		No values specific to phosphorous could be identified. Linking impacts to changes in water quality status suggested	

	Wider impact	Monetary value	Notes	Reference
WI7	Water quality: other	£911.67 t^{-1} (all pesticides)	Value based on costs to water companies of pesticide removal (to meeting drinking water standards) in England between 2004-5 and 2008-9 (£92m) divided by average application of all pesticides in England	Own calculation based on NAO 2010 and FERA 2016
	Water quality: general status change	Rivers: £1.81 hh^{-1} $\%^{-1}$ Lochs: £1.20 hh^{-1} $\%^{-1}$	Public WTP per household per 1% increase in the proportion of rivers or lochs in good status in Scotland River Basin District	Glenk *et al.* 2011
WI8	Soil quality		Increased productivity due to higher yields and/or lower costs. Values will depend on chosen soil quality parameter, its initial starting conditions, crop types and cropping systems	
WI9	Flood management, water use	Average annual damage cost per flooded property (residential and non-residential) based on main (10 highest) areas of risk across 14 Local Plan Districts: Minimum: £462 Maximum: £13,684 Mean: £2,581 Median: £2,136	Value of flood management and water use will be context specific, e.g. the number and types of property protected from flood damage for different severity and probability. Estimated flood damage values are available in the SEPA Flood Risk Management Strategies	SEPA 2015
WI10	Land cover and land use		Value of land cover/use changes will depend on what is being changed. Move to less intensive production may see reduction in gross margins, but increase in co-benefits covered by other WI categories. Similarly a land use change from agriculture to forestry will change both provisioning services and other ecosystem services co-benefits.	

	Wider impact	Monetary value	Notes	Reference
WI11	Biodiversity	Value of BAP habitat improvements (charismatic species): Arable margins: £1.76 - £2.58 ha^{-1} Blanket bog: £25.24 - £36.56 ha^{-1} Hedgerows: £26.01 - £37.68 ha^{-1} Limestone pavement: £42.31 - £57.69 ha^{-1} Lowland heath: £44.73 - £64.77 ha^{-1} Low Hay meadow: £21.90 - £31.43 ha^{-1} Purple moor. grass: £27.96 - £40.55 ha^{-1} Upland calcareous grassland: £15.93 - £23.45 ha^{-1} Upland hay meadow: £11.11 ha^{-1} Upland heath: £29.18 - £42.25 ha^{-1} Coastal floodplain: £38.36 - £55.53 ha^{-1} Fens: £5.52 - £8.29 ha^{-1} Lowland raised bog: £6.36 - £9.54 ha^{-1} Wet reed beds: £15.96 - £23.40 ha^{-1} Native woodland: £33.90 - £49.09 ha^{-1} Arable fields: £0.52 - £0.76 ha^{-1} Improved grassland: £3.07 - £4.44 ha^{-1}	Values are based on a choice experiment that elicited general public WTP for a range of ecosystem services, these values were then allocated to Biodiversity Action Plan (BAP) habitats based on expert assessment of the supply of each ecosystem services. The range of values (where identified) reflects two scenarios: 1) the current 'maintenance' area of habitats achieve BAP targets, 2) 'maintenance' area plus restoration and expansion targets are achieved (as per 2006 UK BAP Habitat Targets, http://jncc.defra.gov.uk/Docs/UKBAP_SpeciesTargets-2006.xls). Single values indicate no difference between scenarios, zero values are omitted. The values listed are total UK values for charismatic (animals, amphibians, birds, and butterflies) and non-charismatic (trees, plants, insects and 'other bugs') species divided by habitat extent to determine per ha values.	Christie *et al.* 2011

	Wider impact	Monetary value	Notes	Reference
WI11	Biodiversity (cont.)	Value of BAP habitat improvements (non-charismatic species): Arable margins: £1.63 - £3.12 ha^{-1} Blanket bog: £6.57 - £13.10 ha^{-1} Hedgerows: £3.88 - £7.74 ha^{-1} Limestone pavement: £7.69 - £19.23 ha^{-1} Lowland calcareous grass: £3.69 - £7.14 ha^{-1} Low dry acid grass: £1.79 - £3.57 ha^{-1} Lowland heath: £9.28 - £18.67 ha^{-1} Low Hay meadow: £6.67 - £13.33 ha^{-1} Purple moor. grass: £6.05 - £12.09 ha^{-1} Upland calcareous grassland: £7.08 - £14.16 ha^{-1} Upland hay meadow: £0.00 - £11.11 ha^{-1} Upland heath: £6.30 - £12.55 ha^{-1} Coastal floodplain: £8.01 - £15.96 ha^{-1} Fens: £1.66 - £2.76 ha^{-1} Lowland raised bog: £3.53 - £7.42 ha^{-1} Wet reed beds: £3.19 - £5.32 ha^{-1} Native woodland: £8.06 - £16.09 ha^{-1} Arable fields: £0.34 - £0.67 ha^{-1} Improved grassland: £0.84 - £1.67 ha^{-1}		
WI12	Animal health and welfare		Impacts on livestock growth (time to target liveweight, liveweight achieved) and vetenary costs. Animal welfare values (beyond production and health impacts) have typically been elicited with reference to production system (e.g. caged versus non-caged eggs, stocking density, environmental enrichment) rather than actual welfare outcomes.	

	Wider impact	Monetary value	Notes	Reference
WI16	Employment	**Type I direct and indirect output multiplier, income effect, employment effect, GVA effect** **Agriculture (SIC 01)** Output multiplier: 1.39 Income effect: 0.20 Employment effect: 16.84 GVA effect: 0.55 **Forestry planting (SIC 02.1, 02.4)** Output multiplier: 1.44 Income effect: 0.34 Employment effect: 18.86 GVA effect: 0.67 **Repair and installation of machinery and equipment (SIC 33)** Output multiplier: 1.25 Income effect: 0.43 Employment effect: 9.70 GVA effect: 0.73	Use of Scottish Input-Output tables and multipliers to determine impacts on employment and incomes. Type I multipliers/effects reflect direct and indirect impacts on industry sector and its supply chain; Type II multipliers also include induced effects throughout the economy. Multipliers and effects stated based on impact of £1m additional final demand in sectors relevant to GHG measures (SIC 33 represents on-farm renewables and AD plant installations). For example, if an additional £5m demand for AD plant installations is identified then direct and indirect impact on employment will be 5 x 9.7 = 49 FTE jobs within the SIC 33 sector and its supply chain; direct, indirect and induced employment throughout the economy will be 5 x 12 = 60 FTEs, indicating an additional 11 FTEs throughout the economy. In terms of employment income, direct and indirect effects will be 5 x 0.43 = £2.15m with a further £0.3m in induced employment income. Care is needed where increases in final demand are not permanent as these employment and income effects will be short-term, there is no proscribed way (i.e. in the Green Book) to account for this.	Scottish Government 2016

	Wider impact	Monetary value	Notes	Reference
WI16	Employment (cont.)	**Type II direct, indirect and induced output multiplier, income effect, employment effect, GVA effect:** **Agriculture (SIC 01)** Output multiplier: 1.51 Income effect: 0.23 Employment effect: 17.93 GVA effect: 0.62 **Forestry planting (SIC 02.1, 02.4)** Output multiplier: 1.65 Income effect: 0.39 Employment effect: 20.68 GVA effect: 0.79 **Repair and installation of machinery and equipment (SIC 33)** Output multiplier: 1.52 Income effect: 0.49 Employment effect: 12.00 GVA effect: 0.88		

	Wider impact	Monetary value	Notes	Reference
WI16	Employment (cont.)	**Type I multipliers for forestry:** **Planting and related services** Income effect: 2.1 Employment effect: 1.4 GVA effect: 1.8 **Harvesting and related services** Income effect: 2.4 Employment effect: 1.8 GVA effect: 2.1 **Type II multipliers for forestry:** **Planting and related services** Income effect: 2.5 Employment effect: 1.5 GVA effect: 2.1 **Harvesting and related services** Income effect: 2.8 Employment effect: 1.9 GVA effect: 2.5		CJC Consulting 2013
WI17	Recycling	Nutrient costs: Nitrogen: £0.67 kg^{-1} nitrogen (£230 t^{-1} ammonium nitrate) Energy costs: Red diesel: £0.50 l^{-1} DERV: £1.17 l^{-1} Electricity: £0.11 kWh^{-1}	Reduction in energy and material (e.g. purchased nutrients) costs.	SAC 2015
WI18	Human health	QALY: £60,000	Impact on both life years and quality of life based on willingness to pay.	Glover and Henderson 2010

	Wider impact	Monetary value	Notes	Reference
WI20	Cultural impacts	Value of improvements to BAP habitats: Arable margins: £0.41 - £0.54 ha^{-1} Blanket bog: £17.00 - £21.66 ha^{-1} Hedgerows: £20.01 - £25.50 ha^{-1} Limestone pavement: £15.38 - £23.08 ha^{-1} Lowland calcareous grass: £12.07 - £15.52 ha^{-1} Lowland heath: £23.52 - £30.06 ha^{-1} Low Hay meadow: £15.24 - £20.00 ha^{-1} Upland calcareous grassland: £16.81 - £21.68 ha^{-1} Upland hay meadow: £11.11 ha^{-1} Upland heath: £27.32 - £34.81 ha^{-1} Coastal floodplain: £22.63 - £28.83 ha^{-1} Lowland raised bog: £8.13 - £10.25 ha^{-1} Wet reed beds: £3.19 ha^{-1} Native woodland: £23.63 - £30.13 ha^{-1} Improved grassland: £3.30 - £4.20 ha^{-1} Urban community woodland: £2,850 ha^{-1} $year^{-1}$ Peri-urban, high facilities: £4,000 ha^{-1} $year^{-1}$ Peri-urban, low facilities: £400 ha^{-1} $year^{-1}$ Rural, high facilities: £2,400 ha^{-1} $year^{-1}$ Rural, low facilities: £180 ha^{-1} $year^{-1}$	Values are based on a choice experiment that elicited general public WTP for a range of ecosystem services, these values were then allocated to Biodiversity Action Plan (BAP) habitats based on expert assessment of the supply of each ecosystem services. The range of values (where identified) reflects two scenarios: 1) the current 'maintenance' area of habitats achieve BAP targets, 2) 'maintenance' area plus restoration and expansion targets are achieved (as per 2006 UK BAP Habitat Targets, http://jncc.defra.gov.uk/Docs/UKBAP_SpeciesTargets-2006.xls). Single values indicate no difference between scenarios, zero values are omitted. The values listed are total UK values for 'sense of place' divided by habitat extent to determine per ha values.	Christie *et al.* 2011 Bateman *et al.* 2011

A3.1 Air quality (WI1-WI4)

The available value estimates for air pollutants are well established and conform to the UK guidance for policy appraisal. The values for each of the emissions include health impacts in terms of morbidity and mortality, in addition those for PM and sulphur oxides include building soiling and impact on materials respectively. The potential for eutrophication and acidification damage to ecosystems are not included. These values are to be used according to the guidance document provided by Defra (Defra 2011b).

A3.2 Water quality (WI5-WI7)

Valuation studies with respect to water quality typically elicit the public's WTP for changes in water quality status: as an indicator this is commonly derived from a combination of underlying biological and chemical parameters. In turn water quality status is combined with further indicators (status of beds and banks, flow, and wildlife) to determine ecological status as required by the Water Framework Directive.

There are advantages to this approach: it reflects an outcome that can be more readily understood by those whose values are being elicited without the need for specialist knowledge; it is less sensitive to the context of individual water bodies (e.g. specific pressures) so values are more widely applicable (in terms of value transfer and evaluating a range of management interventions).

In order to estimate the value of changes in specific water quality pressures, such as diffuse pollution from nitrates or phosphorus, it is necessary to link current water quality status to emissions and determine what change in emissions would be required to achieve the desired status change. From such calculations it is then possible to estimate the values per unit change in emissions.

An alternative approach to valuation is to determine the costs that are imposed by pollutants. For example between 2004-5 and 2008-9 water companies in England spent £189m removing nitrates and £92m removing pesticides from water supplies (NAO, 2010). However there remains a difficulty in relating these figures back to actual emissions of these pollutants such that a unit (per tonne) value can be estimated. Using data on pesticide applications in England (FERA, 2016) to estimate average pesticide applications over the same period as the cost data indicates that the cost to water companies of removing pesticides was £0.91 per kg of product applied (across all pesticide types). This is a crude figure as it does not account for the actual quantity of pesticides reaching water bodies, or specific types of pesticide that may more likely to reach water (due to crop type, targeted pest or solubility), the timing of applications (relative to water flow and dilution) or their environmental persistence.

Applying a similar approach to the cost of removing nitrates from water supply (using the same area that pesticides were applied to combined with typical nitrogen application rates (kg/ha) for tillage crops) gives a value of £4.58 per tonne of nitrogen applied. This clearly is significantly different from the even the lowest nitrogen leaching value (£4,278/t) but reflects the fact that completely different impacts are being valued. The lower value considers only the cost of removing nitrates from public water supplies rather than the broader range of eutrophication impacts, and is based on costs incurred in meeting a standard rather than WTP. It does not account for the actual degree of nitrate leaching as it is applied to total nitrogen applications, i.e. there is a much larger denominator.

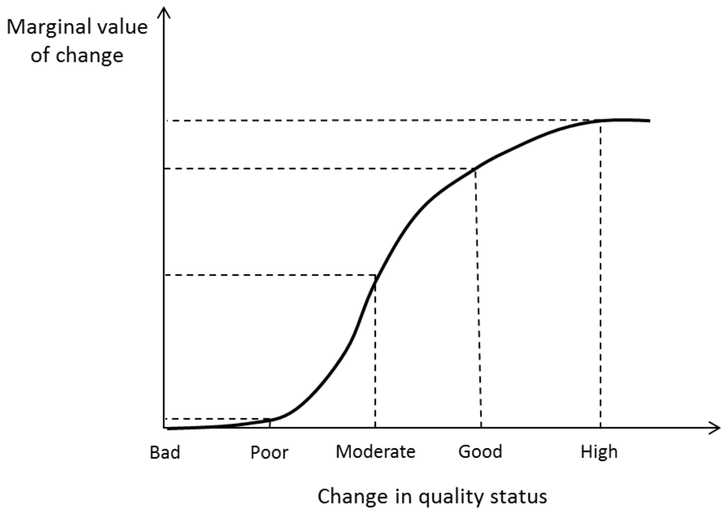

Figure 2 Marginal values for changes in water quality status categories

A3.3 Soil quality (WI8)

Values will depend on chosen soil quality parameter, its initial starting conditions; the nature of management change, and how this impacts quality parameters; crop types and cropping systems. The types of impact observed may include changes in productivity due to higher or lower yields and/or changes in production costs. Improved soil quality may increase soil fertility and structure leading to improvements in growth and yield and reduced nutrient inputs, enhanced workability may also reduce cultivation costs (see values for WI14 material and energy recycling).

There may also be a number of ecosystem service co-benefits that arise from improved soil quality such as better water retention (WI9) and higher biodiversity (WI11).

A3.4 Flood management, water use (WI9)

Value of flood management and water use will be context specific, e.g. the number and types of property protected from flood damage for different severity and probability. Estimated flood damage values are available in the SEPA Flood Risk Management Strategies.

A3.5 Land cover and land use (WI10)

Value of land cover/use changes will depend on what is being changed. Move to less intensive production may see reduction in gross margins, but increase in co-benefits covered by other WI categories. Similarly a land use change from agriculture to forestry will change both provisioning services and other ecosystem services co-benefits.

A3.6 Biodiversity (WI11)

Values are based on a choice experiment that elicited general public WTP for a range of ecosystem services, these values were then allocated to Biodiversity Action Plan (BAP) habitats based on expert assessment of the supply of each ecosystem service. The range of values (where identified) reflects two scenarios: 1) the current 'maintenance' area of habitats achieves BAP targets, 2) 'maintenance' area plus restoration and expansion targets are achieved (as per 2006 UK BAP Habitat Targets, http://jncc.defra.gov.uk/Docs/UKBAP_SpeciesTargets-2006.xls). Single values indicate no difference between scenarios, zero values are omitted.

The values listed are total UK values for charismatic (animals, amphibians, birds, and butterflies) and non-charismatic (trees, plants, insects and 'other bugs') species divided by habitat extent to determine per ha values.

A3.7 Animal health and welfare (WI12)

Impacts on livestock growth (time to target liveweight, liveweight achieved) and veterinary costs. Valued via market prices.

Animal welfare values (beyond production and health impacts) have typically been elicited with reference to production system (e.g. caged versus non-caged eggs, stocking density, environmental enrichment) rather than actual welfare outcomes.

A3.8 Crop health (WI13)

Impacts on crop yield and crop protection costs, specific to crop types. Valued via market prices.

A3.9 Household income (WI14)

Impacts on aggregate household incomes can be estimated using income effects and multipliers from the Scottish IO tables as per WI16 (employment). Specific regional data (e.g. regional SAM models) would be required to determine spatial distribution using this approach unless the aggregate data can be linked to well defined geographical area (thus limiting leakage).

A3.10 Employment (WI16)

Scottish Input-Output tables and multipliers can be used to determine impacts on employment and incomes. Type I multipliers/effects reflect direct and indirect impacts on industry sector and its supply chain; Type II multipliers also include induced effects throughout the economy.

Multipliers and effects stated based on impact of £1m additional final demand in sectors relevant to GHG measures (SIC 33 represents on-farm renewables and AD plant installations).

For example, if an additional £5m demand for AD plant installations is identified then direct and indirect impact on employment will be 5 x 9.7 = 49 FTE jobs within the SIC 33 sector and its supply chain; direct, indirect and induced employment throughout the economy will be 5 x 12 = 60 FTEs, indicating an additional 11 FTEs throughout the economy. In terms of employment income, direct and indirect effects will be 5 x 0.43 = £2.15m with a further £0.3m in induced employment income. Care is needed where increases in final demand are not permanent as these employment and income effects will be short-term, there is no proscribed way (i.e. in the Green Book) to account for this.

Additionally, employment can be valued via WTP, for example rural households were found to be willing to pay £1.08/year for every additional full-time job created by renewable schemes (Bergmann *et al.* 2006).

A3.11 Human health (WI18)

Change in number of cases of ill-health. Economic value can be captured through the valuation of quality life years. It may already be captured with respect to other impacts such as air quality where damage costs reflect morbidity and mortality,

Increased potential for physical and recreational activity (e.g. through afforestation). The economic values of new recreational opportunities will be context specific and reflect location (ease of access, remoteness), available substitutes, site facilities and type of activity that are possible. Diminishing marginal utility (as per water quality) is also likely to be observed with respect to site size.

A3.12 Social cohesion, social engagement (WI19)

Difficult to measure and consequently value.

A3.13 Cultural impacts (WI20)

Values are based on a choice experiment that elicited general public WTP for a range of ecosystem services, these values were then allocated to Biodiversity Action Plan (BAP) habitats based on expert assessment of the supply of each ecosystem service. The range of values (where identified) reflects two scenarios: 1) the current 'maintenance' area of habitats achieves BAP targets, 2) 'maintenance' area plus restoration and expansion targets are achieved (as per 2006 UK BAP Habitat Targets, http://jncc.defra.gov.uk/Docs/UKBAP_SpeciesTargets-2006.xls). Single values indicate no difference between scenarios, zero values are omitted.

The values listed are total UK values for 'sense of place' divided by habitat extent to determine per ha values.

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