Corresponding Author:

Vera Eory
Land Economy, Environment and Society Research Group
West Mains Road
Edinburgh EH9 3JG
Scotland UK

t: +44 (0)131 535 4313
f: +44 (0)131 667 2601
e: vera.eory@sruc.ac.uk
w: www.sruc.ac.uk

Publication date: March 6, 2015

LAND ECONOMY WORKING PAPER SERIES

Number: 85 **Evaluating the use of marginal abatement cost curves applied to greenhouse gas abatement in agriculture**

Evaluating the use of marginal abatement cost curves applied to greenhouse gas abatement in agriculture

Vera Eory

ABSTRACT

Agriculture plays an important role in the transformation towards a 'low-carbon' society. The sector is highly vulnerable to climate variability, and is a significant source of emissions, while at the same time, it has a potential for reducing greenhouse gas (GHG) emissions.

Developing policies to support GHG mitigation emissions requires information on the effectiveness and costs of potential mitigation opportunities. Such information is frequently depicted in marginal abatement cost curves (MACCs), which help to visualise the hierarchy of mitigation measures and their cumulative level of abatement. Like other tools, MACCs have certain limitations. Furthermore, different derivations of MACCs are appropriate to answer different questions. In order to draw both informative and reliable conclusions for policy decisions, the characteristics of the MACCs and the resulting limitations have to be presented clearly.

This paper discusses the main limitations of agricultural MACCs (e.g. wider effects, transaction costs, uncertainty, heterogeneity, non-monetary barriers), reviewing recent methodological developments. Furthermore, it provides guidelines for researchers and policy makers about the choice of methods and the communication of the results in order to improve the use of MACCs in the policy process.

KEY WORDS: marginal abatement cost curves, agriculture, greenhouse gas emissions

Introduction

Climate change is one of the most pressing environmental problems we are facing today. As human activities are the major drivers behind global warming (IPCC 2013), finding alternative ways for production and consumption is crucial in alleviating the harm climate change is likely to cause. However, transforming societies requires both individual and political will, both of them influenced by a range of factors, including the costs and the benefits of the transformation. The assessment of the impacts of alternative pathways on the environment and on the economy is therefore necessary for making informed decisions and designing efficient policies.

One assessment tool to analyse economically optimal greenhouse gas (GHG) abatement is the marginal abatement cost curve (MACC). MACCs have become rather popular in the past decades: they are being used to inform policy both about the estimated optimal level of mitigation effort and about the cost-effectiveness (CE) of possible mitigation measures. Examples include global, continent-level and country-level MACCs in different sectors of the economy – for an overview of the use of MACCs see Kesicki and Stratchan (2011). The MACCs' popularity is mostly due to its ability to convey information in a highly visual, relatively simple way. However, a number of limitations also exist. Addressing all of them at the same time could lead to a highly complex analysis, and difficulty in interpreting results. However, answers to specific policy questions would clearly benefit from addressing related limitations in conventional MACC analysis. This paper seeks to provide suggestions on how agricultural MACCs can be improved so that they provide more comprehensive information to policy makers.

Agricultural GHG MACCs

Agricultural activities on farms has been estimated to account for approximately 11-12% of global and 10% of European anthropogenic GHG emissions {Smith, 2007 843 /id;European Environment Agency, 2014 1584 /id}. These emissions are predominantly in the form of non-CO_2 GHGs: namely N_2O (nitrous oxide) and CH_4 (methane). Most of the agricultural N_2O emissions are produced in soils, with a lesser amount generated during manure management. The main sources are the nitrogen (N) added to soils (e.g. with inorganic and organic fertilisation, crop residues, atmospheric deposition, livestock excreta on pastures) and excreted by livestock in animal houses. Additionally, soluble nitrogen compounds leached into water bodies and gaseous ammonia (NH_3) emissions can also be converted into N_2O. Agricultural CH_4 emissions originate from the digestives system of animals, from manure stores, and from anoxic soils, like wetlands and rice paddies. In animals, methanogenesis happens during bacterial fermentation of feedstuff in the rumen of cattle, sheep and other ruminants, and also takes place, to a lesser extent, in the large intestine of all livestock. In manure management CH_4 is generated during the anaerobic decomposition of livestock bedding and manure, especially in liquid manure stores. CH_4 emissions from rice cultivation are globally important, but marginal in Europe.

MACCs show the cost of reducing pollution by one additional unit as a function of the cumulative pollution reduction achieved against a business as usual scenario (*Figure 1*). When compared to the marginal benefits from pollution reduction, the economic optimum of pollution reduction is defined as the intercept of these two curves (Pearce and Turner 1989). The marginal cost at the economic optimum suggests a pollution price or tax level which would theoretically allow achieving the optimal abatement. MACCs have spatial and temporal context, they refer to a country or specific region, to the whole economy or to a sector and to a time period of either one year or more, often for a time period in the future.

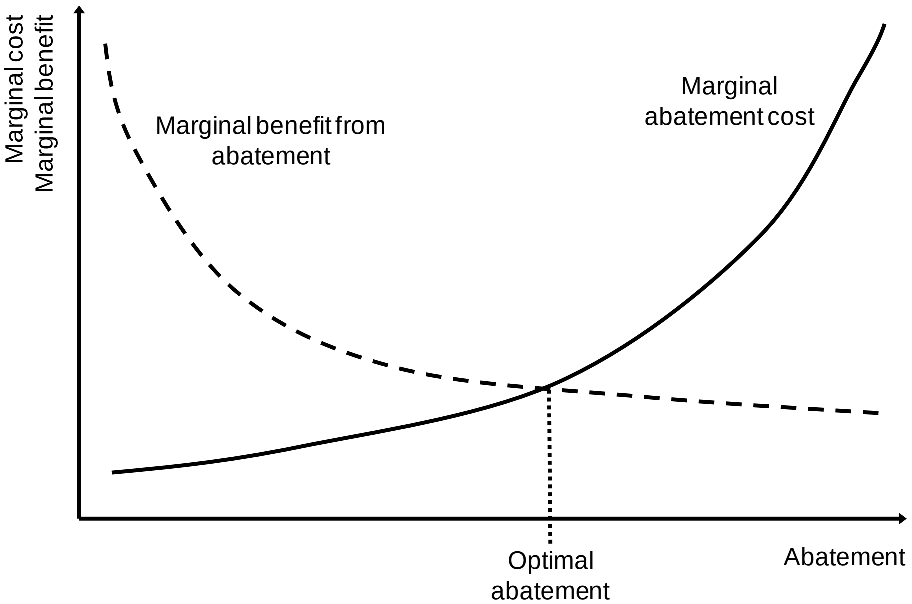

Figure 1. Optimal pollution abatement

Optimal pollution abatement is defined by the marginal cost of abatement and the marginal benefits from abatement (Pearce and Turner 1989)

The marginal cost of abatement can be calculated in various ways. Vermont and De Cara (2010) group MACCs into three main types based on the methodology used to derive the curves. The first is based on micro-economic models, where the behaviour of the economic agents is modelled to derive the marginal cost of abatement, usually assuming profit-maximising agents, with the prices exogenously defined. An example for this approach is a spatial assessment of agricultural non-CO_2 mitigation costs in the EU (De Cara *et al.* 2005). The second approach uses supply side equilibrium models, where prices are endogenous. These models depict how a bigger region's economy or a particular sector of it would behave given the mitigation constraints, like the DICE and RICE models which encompass all major sectors of the global economy (Nordhaus and Boyer 1999), the ASMGHG model depicting the US agricultural and forestry sector (Schneider *et al.* 2007), and the CAPRI model of the European agriculture (Dominguez *et al.* 2009). Finally, in the third group, engineering MACCs compile information on the costs and mitigation effectiveness of a set of mitigation measures to calculate their average CE and then plot these mitigation measures according to increasing CE to derive the MACC. Examples include the McKinsey MAC curves (Naucler and Enkvist 2009) and the sectoral UK MACCs commissioned by the Committee on Climate Change (Collier *et al.* 2013b). The second approach captures economy-wide interactions and is less prone to double counting of emissions or mitigation than the micro-economic and engineering approach. On the other hand, those two approaches are better suited to explore the details of mitigation measures (Kesicki and Strachan 2011).

Addressing the limitations of the MACCs

As any assessment tool, MACCs have their shortcomings (Kesicki and Ekins 2012, Kesicki and Strachan 2011, Vermont and De Cara 2010), and research has been carried out to address a few of these limitations. Nevertheless, many caveats are addressed only sporadically and the methodologies developed have not been taken up widely by subsequent studies. *Table 1* provides an overview of the limitations and relevant research targeting these limitations.

Table 1. Main limitations of the MACCs and examples for research targeting these issues

Main limitations	Examples of studies targeting this limitation	Suggested further research	Category[1]
Boundaries of the analysis are not fit for purpose or not clearly defined	Some studies present MACCs with contrasting boundaries (Schulte *et al.* 2012).	MACCs and CE estimates should be distinguished and estimated at the farm level, domestic and global supply chain level wherever possible.	**
Definitions of the mitigation measures are not specific enough at the farm level	Though some multi-sectoral and global agricultural MACCs assess very broad mitigation options, most sectoral MACCs are more specific.	More accurate mitigation measure definitions during research and intensive dialogue between researchers and stakeholders about the technological details would be beneficial.	*
Discount rate used is not fit for purpose	Some studies estimate the CE and the marginal abatement cost at different discount rates (Moran *et al.* 2008, Pape *et al.* 2008).	Social and private discount rates should be both used to create contrasting MACCs wherever possible.	**
GHG effects are not fully represented	N_2O and CH_4 sources are considered in most studies, while CO_2 emissions and soil and biomass C sequestration are not always. A few studies include all sources mentioned (Golub *et al.* 2009, Schneider *et al.* 2007).	Even though the main agricultural GHGs are N_2O and CH_4, CO_2 emissions and C sequestration should both be mainstreamed in MACCs.	**
Heterogeneity is not represented	Most engineering MACCs are constructed for a region or a country aggregating all agents within a sector, but example exist looking at the heterogeneity of CE (Biggar *et al.* 2013)	Heterogeneity both in unitary abatement and costs are important factors in the potential uptake and total abatement estimates. MACCs for representative farm types, farm sizes or regions can be constructed to reveal the heterogeneity.	**
Interactions between the mitigation measures and their effects on abatement and cost is not represented or not clearly defined	Most studies consider interactions to various extent, though they are not always clearly explained.	Clarity on the interaction methodology is needed. Furthermore, biophysical information on interactions could be used more widely in MACCs.	*

[1] **: most of the MACCs are adequate in this respect, but clearer reporting and communication of the relevant limitations to policy makers is needed;*
***: some MACCs overcome this limitation, but wider uptake of these approaches (when appropriate to the policy question) is needed;*
****: no agricultural MACC has addressed this problem appropriately, according to the knowledge of the author*

Table 1. cont.

Main limitations	Examples of studies targeting this limitation	Suggested further research	Category[1]
Marginal benefits are misrepresented	Studies report the whole MACC curve and thus abatement potential at various marginal benefit values (i.e. CE threshold) can be obtained.	MACC studies should provide the spatially and temporally relevant marginal benefit value.	*
Market effects are not represented in engineering and micro-economic MACCs	Hybrid approaches (a combination of equilibrium and engineering models) exist in other sectors (Andreas Schafer and Henry 2006).	The high differences in abatement rate between equilibrium models on one side and micro-economic and engineering models on the other side (Vermont and De Cara 2010) suggest that a hybrid approach in agriculture would be informative.	***
Non-monetary barriers are not represented	No examples were found.	No study seems to have addressed the non-monetary barriers explicitly in agricultural MACCs. Agent based modelling and multi-criteria analysis might be useful approaches to complement MACCs in this respect.	***
Transaction costs are not represented	Transaction cost studies exist regarding agro-environmental policies (Ducos *et al.* 2009, Krutilla 2011, Mettepenningen *et al.* 2009).	No agricultural MACC seems to have explicitly taken into account transaction costs; transaction costs depending on the policy instrument suggested should be part of the total costs.	***
Wider effects are not represented	MACCs showing some co-effects in physical quantities already exist (Anthony *et al.* 2008, Brink *et al.* 2001, Brink *et al.* 2005, Wagner *et al.* 2012), and non-agricultural studies exist on monetised co-effects (Gielen and Changhong 2001).	No study seems to have included the monetised co-effects into agricultural MACCs; the wider effects should be part of the CE assessment.	**
Uncertainty is not represented	Examples of MACC with uncertainty analysis exist in other sectors and whole economy assessments (2006).	Agricultural MACCs should also include uncertainty analysis.	***

[1] **: most of the MACCs are adequate in this respect, but clearer reporting and communication of the relevant limitations to policy makers is needed;*
***: some MACCs overcome this limitation, but wider uptake of these approaches (when appropriate to the policy question) is needed;*
****: no agricultural MACC has addressed this problem appropriately, according to the knowledge of the author*

As *Table 1* shows, some of these issues have been tackled by a number of authors, while others were hardly, or not at all addressed in agriculture. Three potential problems have been overcome in most agricultural MACCs; these are inaccurate mitigation measure definitions, accounting for interactions and using appropriate marginal benefits. However, reporting and communicating research and its limitations to stakeholders still need to improve in these areas. Five potential limitations (boundaries of the analysis, choice of discount rate, accounting for all main GHG effects, heterogeneity and considering wider effects) have been addressed at least in one study about agricultural MACCs; these methodologies are potentially transferable. A wider future use of these approaches is suggested. Finally, four more limitations (inclusion of market effects, non-monetary barriers, transaction costs and the accounting for uncertainty) have not been addressed in agricultural engineering MACCs to the knowledge of the author. Here a greater research effort is required in the future.

Wider effects

MACCs are designed to look at the CE of reducing one specific type of externality. As opposed to cost benefit analysis (CBA) they have the advantage of looking at the pollution in physical units instead of converting these units into financial units. This prevents introducing an additional uncertainty related to monetising the effects of the pollution. On the other hand, this also constrains the analysis to that single pollutant, without offering an easy way to compare the GHG mitigation efforts with actions to abate other pollutants. Furthermore, the use of physical units does not take into account the effects of GHG mitigation efforts on other pollutants. However, the wider effects can significantly change the results of CE or CBA assessments (Glenk and Colombo 2011, Nemet *et al.* 2010).

Not including the wider effects can become a limitation for two reasons. First, a MACC cannot be used to answer questions about the most efficient allocation of funds among different sustainability goals. However, the MACC approach is still well suited for high-priority issues, like climate change, or where previously agreed pollution thresholds have to be achieved (e.g. regional water pollution), or when the funding sources for the particular pollutant have already been agreed upon.

Second, if a GHG mitigation activity affects other sustainability goals either in a positive or in a negative way, for example reducing GHG emissions but at the same time decreasing diffuse water pollution or increasing food scarcity, the co-effects would make the GHG mitigation activity more or less desirable than a pure GHG CE metric can tell us. Many potential mitigation activities in agriculture have significant co-effects on air pollution (NH_3), diffuse water pollution (nitrate (NO_3^-) leaching), biodiversity and food safety. Assessing these effects together is of high importance. For this purpose a single pollutant MACC can be complemented with qualitative or quantitative assessment of the co-effects, thus providing policy guidance on the overall effects of the mitigation measures.

The research on modelling multiple pollutants has been developing rapidly in the past two decades. There are two divergent technical solutions for the integration. The pollutants can be represented in one single model, as in the GAINS model (Amann *et al.* 2011), where five air pollutants and six greenhouse gases are considered. Alternatively, the effects on different pollutants can be modelled independently, like in Anthony *et al.* (2008), who used six different process models to obtain information on six pollutants. The single model approach might require more investment in model development but can provide better consistency and easier future application, while the benefits of the other approach is that it can include more detailed and robust results on the individual pollutants.

There are two main approaches for the optimisation as well. One method is to optimise for one pollutant while presenting the effects on the other pollutants, see an example by Schneider *et al.* (2007). The other was is looking for optimal solutions integrating the effects of all pollutants in parallel (Anthony *et al.* 2008). This integration can be achieved in three ways. First, if a common pollution unit can be derived for the pollutants in question, a simple MACC can be constructed. This is the case for all GHG MACCs which look at more than one GHGs: the common metric is CO_2-equivalents; non-CO_2 gases usually being converted by using global warming potential (GWP) values. Alternative metrics are also in use, such as radiative forcing (van Vuuren *et al.* 2006). The choice of metric makes a difference in the importance of the different GHGs over short- and long time horizons (Reilly *et al.* 1999). Prioritising mitigation measures within agriculture and between agriculture and other sectors has to take into account this issue, as the majority of agricultural GHG emissions both globally and in Europe are in the form of non-CO_2 gases CH_4 and N_2O.

Second, when no physical unit can be easily constructed for the integration of different pollutants, a composite indicator can be constructed (OECD 2008). To do so, the effects of the various pollutants have to be normalised in order to allow comparison (e.g. by comparing each to a respective target, like a damage threshold, or, if such a target value is not available, using standardisation or min-max techniques). Weighting and aggregation rules also have to be set. Preferential weighting of the pollutants (and other indicators, including social targets and costs) can be developed in a multi-criteria analysis approach, where the importance of each indicator in the evaluation is set by the decision makers or the analysts (Linkov *et al.* 2006). The approach allows for including effects which only have semi-quantitative information and is well-suited to reflect stakeholders' preferences. Multi-criteria analysis has been used in the assessment of GHG mitigation policy instruments (Konidari and Mavrakis 2007) and adaptation strategies (de Bruin *et al.* 2009).

Finally, the effects on multiple pollutants can be integrated via converting the physical units to monetary values (Winiwarter and Klimont 2011). This is possible if the damage cost estimates of the pollutant are available. The monetary value of the damage avoided can be added to the financial costs of the mitigation measure and then evaluated against the primary pollution thus conducting a CE analysis extended to co-effects. On the other hand, if all the environmental effects are converted into monetary terms, a cost benefit analysis becomes possible (Pretty *et al.* 2000). While the results of such approaches can be presented in visual ways which are easy to understand, the choice of damage values might have a significant impact on the results. This can limit the usefulness of the method particularly when the damage values are very uncertain, have a high spatial or temporal variability or if a strong threshold effect exists.

Transaction costs and the cost-effectiveness of policy instruments

Agriculture, consisting of a very heterogeneous group of agents and burdened with the difficulties of spatially and temporally highly variable GHG emissions, is a sector where market-based instruments are usually very costly to set up. This, combined with other barriers in international negotiations, creates a situation where promoting mitigation via voluntary or targeted obligatory regulations are the favoured policy instruments over market-based instruments (Beddington *et al.* 2012, Kasterine and Vanzetti 2010). The development of such policy instruments, particularly the prioritisation of mitigation measures for compulsory and voluntary regulations, requires detailed information on the mitigation measures. MACCs derived from equilibrium models provide information for the evaluation of general policy scenarios (e.g. a carbon tax or a subsidy), but are less suitable to the comparative analysis of mitigation measures, which, in turn, could feed into regional policy development. Engineering MACCs are capable of informing this type of policy development well, though two considerations have to be addressed.

The effectiveness of policies in terms of generating additional abatement is an important factor in policy CE. Policy instruments operating on the basis of non-subsidised voluntary uptake are likely to achieve lower uptake than policy instruments providing financial subsidies and thus transferring part of the private costs to public costs. Moreover, compulsory regulations might lead to even higher uptake. Engineering MACCs work on a basis of an assumed uptake rate, which has a major influence on the abatement achievable. In some MACCs 100% uptake is assumed, i.e. the results present the maximum technically available abatement (Moran *et al.* 2008), while other MACCs divide the 100% uptake evenly between the measures (DeAngelo *et al.* 2006), or they assign uptake values to individual mitigation measures (Pellerin *et al.* 2013). However, rarely do they link their assumptions to policy instruments to be used in the future. Such assumptions on policy compliance can be derived from *ex post* assessments of similar environmental policies (Mettepenningen *et al.* 2009) or can be estimated via econometric models (Ducos *et al.* 2009). Additionally, the level by what public agents take over cost elements from the private sector has a profound effect on uptake, and for this reason it is good practice to make a distinction between private and public costs in the MACCs.

Second, transaction costs, which go beyond the technical implementation of the mitigation measures, can be of high importance. These are the costs related to policy making from the planning phase through enforcement, and can range between 21-50% of total costs (Coggan *et al.* 2010). They include *ex ante* costs of establishing environmental entitlements (e.g. information collection, legislation development) and *ex post* costs of implementation (e.g. administration, contracting, monitoring, enforcement) (Krutilla 2011, McCann *et al.* 2005). Although most of these costs are usually public costs, private agents also incur part of them mainly in the form of time required for information gathering and record keeping. Estimating these costs is often difficult, but including them in the calculations can improve the abatement and cost projections.

Overall, an engineering MACC can be used to inform *ex ante* assessment the CE of environmental policies by first producing a maximum technical potential abatement MACC and then building in information on policy packages (i.e. clearly defined policy instruments targeting a detailed set of mitigation measures, with an estimated level of uptake and compliance, complemented with transaction costs estimates).

Uncertainty

Robust policies, which are able to achieve their objectives across a range of possible futures, have to be developed by taking into account uncertainties (Lempert and Schlesinger 2000). Uncertainty analysis is becoming part of economic assessments looking at GHG mitigation, particularly in global, multi-sector models and in the energy sector (Peterson 2006). However, to date, research on the economics of GHG mitigation in agriculture has rarely included uncertainty analysis, even though this would be of high importance to inform regional, mitigation measure specific policy design. The heterogeneity of the sector and the spatial and temporal variability of emissions pose particular challenges for uncertainty assessments.

Uncertainties associated with uptake levels, mitigation potential and costs of future GHG mitigation measures all contribute to the uncertainty of the MACC. They are a result of both the stochastic nature of and our limited knowledge about the underlying biogeochemical, economic and societal processes, human behaviour and politics. On one side, biogeochemical processes have a significant influence on land use activities, farm management decisions and associated emissions. Their uncertainties filter through to the uncertainties in the effectiveness of mitigation measures. One example is the N_2O emissions arising from N fertiliser application. These emissions vary significantly with the weather conditions under static management, and at the same time weather conditions also define management decisions about fertilisation, adding another layer of stochasticity to the GHG emission and mitigation. On the other side, the economic and policy environment are also crucial in land use decisions, and their uncertainty contributes to the MACC uncertainty as well. For example price fluctuations, the uncertainty in future changes in policy regulations (e.g. subsidies for renewable energy or Common Agricultural Policy (CAP) payments) and farmers' reaction to these changes are all important factors in uncertainty.

Some of these uncertainties can be quantified (expressed as probabilities) and hence included in quantitative models, although information on them often does not yet exist in the scientific literature. Other uncertainties cannot be quantified statistically; this is particularly the case for complex models predicting the future (Hallegatte *et al.* 2012) and for value uncertainty, like the choice of discount rate.

The MACC methodology is able to accommodate information on quantifiable uncertainty of the optimal abatement and the CE of the mitigation measures and can convey it in a relatively simple language. Uncertainties which cannot be quantified have to be presented alongside the results as well so that policy makers and other users of the MACCs would be fully aware of the applicability and robustness of the results. Not overlooking the difficulties of communicating uncertainty between scientists and policy makers, a mutual engagement from both sides is required to widen the use of this type of information in policy making (Smith and Stern 2011).

Boundaries

MACCs relate to a sector or the whole economy of a region, country or group of countries, to a particular time period, and they also have boundaries in terms of what cost elements and emission sources are included. According to these features they can be useful in different policy contexts.

MACCs depicting national mitigation effort in a group of countries can inform international agreements and regulations, like policies in the European Union (Blok *et al.* 2001). Similarly, a series of sectoral MACCs related to an economy can be used for designing sector-specific targets, e.g. the UK Carbon Budgets (Anon. 2014). However, to avoid double counting of mitigation, the boundaries among the set of MACCs have to be clearly defined and stay within their respective regional and sectoral limits. In such a methodology mitigation measures are evaluated within the relevant spatial/sectoral boundaries without considering effects beyond. For example the effects on emissions related to soya production of reducing N in livestock diets are not included, neither the changes in emissions from N fertiliser production due to the reduced application of synthetic N fertilisers. Taking into account the full GHG effects of mitigation measures are possible with a life cycle analysis (LCA) approach. As Schulte *et al.* (2012) presents, the resulting abatement potential and CE can be different from the conventional MACC. While the national and sectoral approach is important for allocating mitigation effort between countries and sectors, decision makers should not solely rely on them. The assessment should be complemented with LCA-based results to avoid potential emission leakage, where unintended additional emissions happen in other countries or in other parts of the supply chain.

A related issue is the methodology used to calculate the baseline GHG emissions and the potential mitigation, particularly the difference between IPCC and other approaches. The national GHG inventories calculate agricultural emissions by a combination of methodologies called Tier 1, Tier 2 or Tier 3 methods (IPCC 2006), and consider mitigation where there is a robust evidence to justify the effect. As these national inventories provide the starting point for international agreements, policy makers would aim to achieve mitigation which can be reflected in these inventories. On the other hand, MACCs explore further mitigation measures which currently might lack robust, quantified evidence on the overall mitigation effect. Furthermore, the abatement potential of an mitigation measure is different depending on which IPCC methodology is used, and, as discussed also above, differs further with other methodologies (Lengers and Britz 2012). Therefore, policy makers would find it useful to know how much of the abatement can be represented in the national inventory, what methodological developments are needed to reflect all robust mitigation in the national inventory, and what the additional emission consequences are of those mitigation measures which are not represented on a particular MACC or in the national inventory.

A similar dilemma exists for the choice of production and consumption based emission accounting. Consumption based emissions differ from production based emissions in that they include the embedded emissions of imported goods and services and exclude the emissions related to the production of exported goods and services. Production related emissions are higher than consumption related emissions in China and Russia, while most of the Kyoto Protocol Annex I countries show the opposite pattern (Lenzen *et al.* 2013). The gap between consumption and production based emissions have been widening in the past years in the UK (Collier *et al.* 2013a). Most agricultural MACCs have been using a production based accounting. Even those, which consider one or more mitigation measures targeting food consumption, look at production based emissions (Westhoek *et al.* 2014), and do not account for imports and exports of agricultural products. The production based approach is suitable for most of the policy options as these policies mostly targeting the farmers rather than the consumers, but for the assessment of policy instruments targeting consumption further developments are needed in the MACCs.

A final boundary concern is the temporal relevance of the MACCs. Annual MACCs (or a series of annual MACCs over a time period) can be used as snapshots of abatement potential and costs when planning for reduction targets and milestones. However, cumulative MACCs (integrating abatement potential over a longer period of time) can be also useful if mitigation measures differ significantly in how their costs, mitigation efficiency or uptake changes over time. While shorter-term MACCs, limited to individual sectors and regions, can feed into rapid policy design, longer term and economy-wide MACCs have also be considered to avoid lock-in situations. Lock-in situation can occur if a pathway, which is favourable in the short-term, is followed and makes it costly to change to another set of actions, which are more favourable in the long-term (Vogt-Schilb and Hallegatte 2011). Even though many of the mitigation measures suggested in agriculture are easily reversible (e.g. the administration of animal feed additives), longer term investments like establishing or improving soil drainage, irrigation, animal housing or anaerobic digestion might create pathway-dependency. These can become obstacles when system transitions (e.g. changing the location of cropping and grazing areas) become preferable (especially due to changing climatic conditions).

Definitions of the mitigation measures

Engineering MACCs are based on the assessment of technological or management options, which are assumed to be replacing current technology or management and thus provide mitigation measure. Due to the differences in farming practices, the categorization of the mitigation measures is not without difficulties. Moreover, scientific reports and knowledge exchange documents all differ in terms of the broadness and accuracy of their mitigation measure definitions. For example 'nutrient management' can be considered as one broad mitigation measure, but often it is separated into five, ten, or more mitigation measures, like 'Reduce the rate of mineral fertiliser by more effectively adjusting yield targets', 'Improved timing of mineral fertiliser N application' or 'Use nitrification inhibitors'. These mitigation measures are sometimes further divided, like the 'Use nitrification inhibitors' can be disaggregated according to the type of fertiliser it is used on (mineral or organic). Though the context specific development of mitigation measures is essential and a universal mitigation measure list do not exist (Smith 2011), the diversity in the definitions makes the comparison between studies difficult.

A further complication is that very often the choice between practices is more of a continuous than of a discrete nature. A typical example is the timing of nitrogen fertilisation. Though a discrete choice exists between applying the whole amount of fertiliser at once as opposed to splitting it into two (or more) applications, the exact timing of the application relative to the growth stage of the crop is almost a continuous choice. Similarly, changing the proportion of ingredients in the livestock diet is a continuous choice. For instance, 'Increasing concentrates in the diet' is widely featured as a mitigation measure, but studies very rarely provide detailed advice on what should be the composition of these concentrates and what proportion should they make up in the diet. The choices and circumstances in the previous examples are all important driving factors for GHG emissions, but cannot be easily defined and described. These – practically necessary – simplifications increase the uncertainty in the abatement potential estimates and at the same time enhance the risk of miscommunication between researchers and stakeholders, particularly farmers.

Discount rate

The choice of discount rate is a much debated and very important question in environmental CBA and cost-effectiveness analysis (CEA). The discount rate reflects the time preference of the individuals and society: the higher the discount rate, the more emphasis is put on costs and income happening earlier. For private investments normally the return on investments is used as discount rate, representing how much the money could grow if invested in the market. Contrastingly, long-term public investments are discounted with a lower discount rate to represent the inter-generational equity better. This social discount rate can be constructed as a declining discount rate as opposed to a constant low discount rate (Arrow *et al.* 2013). Individuals might also have discount rate preferences depending on the time frame considered (Grijalva *et al.* 2014). The existence of these two contrasting discount rate, private and social, poses a problem to MACC analysis: for example, shall afforestation costs and benefits be discounted with a private or a social discount rate? Which discount rate shall be used when assessing the construction of anaerobic digesters? The answers would partially depend on whether the investment is expected to be financed by private individuals or from public money. As MACCs often do not refer to a very particular policy environment where the share of public *versus* private funding is determined for each mitigation measure, the choice of discount rate remains unresolved. However, alternative MACC evaluations can be presented based on the different discount rates and this can inform policy makers about how the CE of the mitigation measures are different from the perspective of the farmers and of the public budget.

GHG sources

As discussed above, agricultural GHG emissions consist of N_2O, CH_4, and only to a smaller extent of CO_2. On the other hand the importance of agriculture for N_2O and CH_4 emissions is high. Consequently, the main focus of MACC studies has been on N_2O and CH_4 mitigation, with little or no attention to CO_2 emissions and C sequestration. This might be unintentionally encouraged by the IPCC GHG inventory methodology, where some important CO_2 sources and CO_2 sinks (namely emissions and sequestration from agricultural land use change and emissions from fuel and energy use) are reported outside of the 'Agriculture' category.

Though by now most agricultural MACCs consider CO_2 as well as N_2O and CH_4, changes in biomass and soil C content is often neglected, even though globally, the majority of the economically efficient abatement arises from the increase in soil C stocks (Smith 2011). This suggests that the soil and biomass C stock changes are of importance for MACC studies, and neglecting them might result in underestimating the abatement potential.

Heterogeneity

The heterogeneity in the farming system (regarding farming systems, practices, climatic and soil conditions and farmer behaviour) is reflected in the difference in the pollutant profiles of the various farms (Dalgaard *et al.* 2011). Beyond the heterogeneity in emissions, the sector also exhibits heterogeneity in resource constraints (e.g. access to labour and capital) and in the financial structure of the farm. Altogether, these result in the heterogeneity of abatement and abatement costs. As engineering MACCs use estimated average values to describe the sector, the range of potential differences in abatement and CE of the mitigation measures is most often overlooked, one of the few exemptions is the CE analysis of mitigation options in the US agriculture (Biggar *et al.* 2013). Micro-economic and equilibrium models represent a range of farms, farm types or agricultural regions and therefore are able to present the heterogeneity of the abatement costs (De Cara and Jayet 2000), though not for individual mitigation measures. Without information on the level of heterogeneity and the differences between farm types, farm sizes, etc. the effectiveness of policy instruments targeting specific mitigation measures might be lower than expected.

Interactions

mitigation measures often involve making management or infrastructural changes on the same production factors or processes. To construct a MACC, this necessitates the mitigation measures to be considered as processes interacting with each other, both in terms of mitigation effect and costs. Assessing the mitigation measures independent of each other leads to a so-called stand alone CE analysis of the mitigation measures, which is informative if it is likely that agents will only implement one or very few mitigation measures. However, stand alone assessment is not suitable for deriving a cumulative abatement potential due to potential double counting, or not accounting for mitigation and costs. MACCs based on equilibrium models and micro-economic models inherently capture part of these interactions, based on how the GHG emissions are represented in the models. Those interactions which relate to resource use belong to this group, for example the N_2O mitigation potential which can be achieved by optimised N fertilisation of grasslands is reduced if the share of legumes in the swards has been increased – this is usually captured in the models if the fertilisation rate on grass-legume swards is lower than on pure grass swards. Other interactions can only be included in these models by additional modifications in the model, for example if the N flow is not built in the model, then the reduced N_2O abatement achievable with slurry cooling having already decreased the N content of the diet is not automatically modelled. On the other hand, engineering MACCs do not include any interactions by default, but they have to be built in them via, for example interaction factors which alter the abatement potential or costs of a mitigation measure based on which other mitigation measures have already been implemented (i.e. all of the mitigation measures which are to the left on the MACC from the mitigation measure in question).

Marginal benefits of mitigation

To attain the economically optimal abatement the marginal costs of GHG mitigation have to be compared with the marginal benefits. GHG mitigation benefits arise from the avoided impacts like changes in global temperature, extreme weather events, see level rise and sea acidification. The marginal benefits are a function of the emission level, i.e. the amount of emission abated (Tol 2005), the location of the benefits (Anthoff *et al.* 2009), and the timing of the mitigation (Frankhauser and Tol 1996). Though these considerations are important in long-term and international decisions, they are rarely considered in MACCs, where usually the marginal benefit is approximated with a constant. This simplification is partly appropriate for MACCs carried out at a smaller scale, e.g. at national level, assuming that the mitigation level does not have a significant effect on the global emissions – this assumption corresponds with the fact that policy decisions about low carbon efforts are ultimately determined at a national level (Anthoff and Tol 2010). However, marginal benefits can change considerably, for example Price *et al*. (2007) estimation for the social price of carbon changes from £18.6 t CO_2e^{-1} to £59.6 t CO_2e^{-1}. Thus the economically efficient abatement potential can change considerably over time as well. A representation of this temporal change is possible by constructing a set of annual MACCs as snapshots covering a time period, each of them using the relevant carbon price.

Market effects

Agri-environmental policies targeting GHG emissions are likely to impose various changes in the costs of crop and livestock production, which, in turn, might lead to changes in the supply of agricultural products, especially if the policy impacts on a substantial number of farms. A shift in the supply will eventually lead to changes in the agricultural commodity prices, with a feedback on the whole sector and beyond. By definition, micro-economic and engineering MACCs are not capturing these feedback loops, and therefore their estimates are only valid within the assumption that prices will not be significantly affected by the mitigation policies. On the other hand, in equilibrium models these prices are endogenously defined, and their results account for the market effects.

Non-monetary barriers

MACCs capture the technological costs, for example investment in new machinery and savings in resource use. As mentioned above, other cost elements, like transaction costs and policy costs are usually not considered, and, as they are based on some form of profit maximisation assuming rational agents, neither behavioural barriers are included. In reality, farmers have a mixture of objectives which includes profit maximisation but also risk aversion, environmental attitudes and social context as important factors in decision making (Pannell *et al.* 2006). These factors, along with lack of information, regulatory and market constraints, can create barriers for uptake of mitigation measures beyond the cost aspects (Feliciano *et al.* 2014). This phenomenon is most visible in the presence of 'win-win' mitigation measures on the engineering MACCs. Win-win mitigation measures are estimated to have negative CE, i.e. they are estimated to generate savings as opposed to costs. Assuming rational agents the win-win measures can only be understood as a consequence of underestimated costs, but the existence of non-monetary barriers can explain their appearance on the MACCs. When policy makers consider the low hanging fruits, or, indeed, any other mitigation measure, information on these barriers is needed to complement the CE results in order to design efficient policies.

Conclusions

MACCs and CE assessments have proved to be popular instruments for informing environmental policy decisions. The usefulness of information provided by MACCs is maximised if users of this information are aware of the relevance and limitations of the analysis and, where possible, use alternative forms of MACCs, and complement their evaluation with other types of assessments, depending on the policy question in place.

Guidance – intended for policy makers and other stakeholders – on how the limitations can affect the cost, cost-effectiveness and abatement estimates of the MACCs is presented in *Table 2*. The table also provides practical guidance on how to minimise these problems.

Table 2. Summary of the main limitations of the MACC with suggested approach when providing information to policy decisions

Main limitations	Potential problems	Unitary CE[a]	Economically efficient mitigation	Suggested policy approach
<u>Boundaries</u> of the analysis are not fit for purpose or not clearly defined	If the boundaries are defined as the farm and/or domestic emissions, then there is a potential for emission leakage, i.e. some mitigation measures with seemingly low CEs can be supported while they increase emissions outwith the farm gate or in other regions.	Over- or under-estimated	Over- or under-estimated	To assess which mitigation measures are the most cost-effective and provide the highest abatement at the global level use analysis looking at the whole supply chain and global effects. If not available, obtain quantitative assessment about the potential effects beyond the farm gate.
	If the boundaries are broader than the farm gate and/or domestic emissions and at the same time the analysis is cross-sectoral or covers multiple regions then part of the mitigation potential might be double counted.	Over- or under-estimated	Over- or under-estimated	To assess effort sharing between sectors or regions use MACCs which stay within the boundaries of the individual sectors/regions.
<u>Definitions of the mitigation measures</u> are not specific enough at the farm level	Communication between researchers, farmers, policy decision makers and other stakeholders is impeded. Actual changes in farming practices might differ from what had been suggested at the first place, likely reducing the mitigation effect.	No bias	No bias	Ensure that communication towards stakeholders is specific in articulating the suggested technical and management changes on farm.
<u>Discount rate</u> used is not fit for purpose	Private or public costs are under- or overestimated (especially for capital intensive mitigation measures), inter-generational equity is not addressed.	Over- or under-estimated	Over- or under-estimated	Use MACCs with contrasting (private and social) discount rates. If possible, use CE and uptake estimates where mitigation measures likely to be publicly/privately funded are assessed with a social/private discount rate, respectively.
<u>GHG effects</u> are not fully represented	Unintended emission or not-accounted mitigation might occur, thus the mitigation potential of some mitigation measures would be under- or overestimated.	Over- or under-estimated	Over- or under-estimated	Use MACCs considering changes in C stores (both soil and biomass) alongside N_2O, and CH_4, or, if not available, obtain quantitative assessment about which mitigation measures have potentially high effect on C stores.

[1] *Note that the higher the CE the less favourable the mitigation measure is*

Table 2. cont

Main limitations	Potential problems	Unitary CE[a]	Economically efficient mitigation	Suggested policy approach
<u>Heterogeneity</u> is not represented	The differences in CE and mitigation potential between regions, farm types etc. are overlooked, therefore policy instruments might fail in some areas. Farms where the CE of a mitigation measure is higher than the average CE would show very low uptake.	No bias	Over-estimated	Use MACCs assessing heterogeneity in costs and abatement. If not available, flexible policy instruments can be designed to support mitigation measures with a wide range of private CE, e.g. linking financial support to expenses and opportunity costs occurred rather than providing a flat rate support.
<u>Interactions</u> between the mitigation measures and their effects on abatement and cost is not represented or not clearly defined	MACC is presented without accounting for interactions, therefore potentially double-counting part of the mitigation potential.	Under-estimated	Over-estimated	Only use MACCs which account for interactions when assessing total regional abatement. On the other hand, use CE and abatement of the individual mitigation measures (or a small package of mitigation measures) in regional policy design if realistically each individual farmer will not implement more than a few mitigation measures.
	The CE estimates calculated with considering interactions are used to assess CE in situations where the likely uptake would be limited to a few mitigation measures (therefore very limited interactions would occur).	Over-estimated	Under-estimated	
<u>Marginal benefits</u> are misrepresented	Incorrect CE threshold is used for defining the economically efficient mitigation	No bias	Over- or under-estimated	Ensure that the CE threshold used is consistent with the spatial and temporal relevance of the MACC; if possible, obtain sensitivity analysis results for the economically efficient mitigation at different thresholds.
<u>Market effects</u> are not represented in engineering and micro-economic MACCs	Potential effects on commodity markets are not captured and therefore some effects on food security, farm profitability and also on the CE of the mitigation measures might be overlooked.	Under-estimated	Over-estimated	Use general equilibrium ('top-down') MACCs to complement engineering ('bottom-up') MACCs, especially if large-scale changes in the amount of products or in farm finances is likely to happen.

[1] *Note that the higher the CE the less favourable the mitigation measure is*

Table 2. cont.

Main limitations	Potential problems	Unitary CE[a]	Economically efficient mitigation	Suggested policy approach
<u>Non-monetary barriers</u> are not represented	Voluntary uptake might be lower than predicted (and compulsory uptake might be more burdensome).	No bias	Over-estimated	Complement MACC analysis with analysis of the barriers of the different mitigation measures. Ideally, uptake estimates should take into account the potential main barriers in relation to each mitigation measure and policy instrument. Higher stakeholder involvement can help to improve the estimates.
<u>Transaction costs</u> are not represented	If the private transaction costs are not captured, then the voluntary uptake might be lower than predicted (and compulsory uptake might be costlier). If the public transaction costs are not captured, then the cost of the policy instruments are underestimated, which might result in overspending or underdevelopment of the policy instruments.	Under-estimated	Over-estimated	If no MACC is available where transactions costs are estimated and built in, then use qualitative assessment of the likely level private and public transaction costs in relation to mitigation measures and policy instruments.
<u>Wider effects</u> are not represented	Integrated policy development is impeded: mitigation measures with negative co-effects might be supported, mitigation measures with positive co-effects might be overlooked.	No bias	Over- or under-estimated	Ensure that all the regionally/globally important environmental and societal effects are assessed, either included in the costs/benefits, or in physical terms. If no quantitative results are available, use a qualitative overview of the potential synergies and trade-offs.
<u>Uncertainty</u> is not represented	Not robust enough policy instruments, possible future changes in economic or climate/weather conditions can drastically reduce the CE of the policy instruments. If costs or baseline uptake underestimated or mitigation overestimated: costly or low potential mitigation measures might be overfunded, and *vice versa*.	Over- or under-estimated	Over- or under-estimated	Uncertainty analysis can be carried out on the MACC (e.g. Monte Carlo analysis). Alternatively robust decision making techniques can be used in policy development. Finally, sensitivity analysis can still reveal how the CE or the abatement potential might change in case of over- or underestimated input variables.

[1] *Note that the higher the CE the less favourable the mitigation measure is*

The overall conclusion can be made that agricultural MACCs can be improved so that to provide more comprehensive information to policy makers. Some improvements are to be made in communication between scientists and stakeholders, like the definitions of the mitigation measures, or the boundaries of the analysis. Other potential limitations are already addressed in agricultural MACCs, either widely (accounting for interactions, choice of discount rate, accounting for all main GHG effects) or in a few studies. It is suggested that these methodological improvements should be applied more widely. Quick further progress can be achieved with the more widespread application of the relatively less resource intensive methodological improvements, like creating a private and a social MACC using relevant discount rates. Other improvements require the introduction of more complexity in the models (like addressing the problems around the boundaries of the analysis, wider effects, accounting for uncertainty). Admittedly, the quantitative representation of all these issues in parallel could provide computational difficulties and, could also impede the understanding of the results. A pragmatic approach is suggested therefore, whereby specific quantitative methodologies are used to answer specific policy questions, having the results complemented with qualitative analysis related to other limitations.

16

Boundaries

- Are the results suitable more for sectoral/regional analysis or to look at the global GHG effects?

Definitions

- Provide detailed technical description of the mitigation measures

Discount rate

- Private or social discount rate is used?
- Which are the mitigation measures most affected by the choice of discount rate?
- Are the assumptions on uptake aligned with the discount rate used?

GHG sources

- What GHG emission sources are included?

Heterogeneity

- Is there likely to be significant heterogeneity in the results?
- What are likely to be the main sources of heterogeneity?
- Is the limitation regarding heterogeneity addressed?

Interactions

- How are interactions regarding both emissions and costs included?
- What is the basis for mitigation calculation (IPCC, biophysical modelling, etc.), and how do these deal with interactions regarding e.g. N flow, livestock dietary options?

Marginal benefits

- To which year and region does the CE threshold used refer?

Market effects

- Are market effects considered and to what extent?

Non-monetary barriers

- Are any non-monetary barriers included (e.g. via uptake rates or as utility maximisation)?

Wider effects

- Are any wider effects included either quantitatively or qualitatively (e.g. through the pre-selection of mitigation measures)?

Uncertainty

- Has a sensitivity analysis or an uncertainty assessment been done?
- What are the assumptions the results are most sensitive to?
- What is the confidence interval of the results?

Figure 2 Guideline for MACC analysis attributes to be disclosed when reporting results

17

MACCs are useful for informing the policy process, but should be used with full awareness of their relevance. Researchers providing MACC estimates are responsible for providing a clear indication of the important aspects of the MACCs. Without these pointers there is an increased likelihood of misinforming decision makers and designing inefficient policies. *Figure 2* a guideline is suggested about the reporting of the MACC methodology. Following this guideline could facilitate future users' understanding of how the choice of methods affects the validity of the results. The questions presented here are proposed to be addressed in a summary section of all future agricultural MACC reports.

Going forward it is important to keep in mind that CE and MACCs are able to explore and present important aspects of potential pollution reduction activities, but these aspects have to be complemented by other assessments. Furthermore, most importantly, MACCs have to be embedded in a decision making process whereby all the important social, economic and environmental aspects are explored by the stakeholders.

Acknowledgement

This research was undertaken within the Scottish Government Rural Affairs and the Environment Portfolio Strategic Research Programme 2011-2016 and with funding provided to ClimateXChange (http://www.climatexchange.org.uk/). For more information please see: http://www.scotland.gov.uk/Topics/Research/About/EBAR/StrategicResearch/future-research-strategy/Themes/ThemesIntro. Further funding was provided by the AnimalChange project which received funding from the European Community's Seventh Framework Programme (FP7/ 2007-2013) under the grant agreement n° 266018.

18

References

Anon. (2014) The Fourth Carbon Budget – reducing emissions through the 2020s, Committee on Climate Change.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Hoglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schopp, W., Wagner, F. and Winiwarter, W. (2011) Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environmental Modelling & Software 26, 1489-1501.

Andreas Schafer and Henry (2006) Experiments with a hybrid CGE-MARKAL model. The Energy Journal Hybrid Modeling, 171-178.

Anthoff, D., Hepburn, C. and Tol, R. S. J. (2009) Equity weighting and the marginal damage costs of climate change. Ecological Economics 68, 836-849.

Anthoff, D. and Tol, R. S. J. (2010) On international equity weights and national decision making on climate change. Journal of Environmental Economics and Management 60, 14-20.

Anthony, S., Duethman, D., Gooday, R., Harris, D., Newell-Price, P., Chadwick, D. and Misselbrook, T. (2008) Quantitative assessment of scenarios for managing trade-off between economics, environment and media, Report No Defra WQ0106 (Module 6), Defra, ADAS, North Wyke Research.

Arrow, K., Cropper, M., Gollier, C., Groom, B., Heal, G., Newell, R., Nordhaus, W., Pindyck, R., Pizer, W., Portney, P., Sterner, T., Tol, R. S. J. and Weitzman, M. (2013) Determining Benefits and Costs for Future Generations. Science 341, 349-350.

Beddington, J. R., Asaduzzaman, M., Clark, M. E., Fern+índez Bremauntz, A., Guillou, M. D., Howlett, D. J. B., Jahn, M. M., Lin, E., Mamo, T., Negra, C., Nobre, C. A., Scholes, R. J., Van Bo, N. and Wakhungu, J. (2012) What next for agriculture after Durban? Science 335, 289-290.

Biggar, S., Man, D., Moffroid, K., Pape, D., Riley-Gilbert, M., Steele, R. and Thompson, V. (2013) Greenhouse gas mitigation options and costs for agricultural land and animal production within the United States, Report No Contract No. AG-3142-P-10-0214, ICF International, U.S. Department of Agriculture Climate Change Program Office Washington, DC.

Blok, K., de Jager, D., Hendriks, C., Kouvaritakis, N. and Mantzos, L. (2001) Economic Evaluation of Sectoral Emission Reduction Ojectives for Climate Change, European Commission.

Brink, C., Kroeze, C. and Klimont, Z. (2001) Ammonia abatement and its impact on emissions of nitrous oxide and methane--Part 2: application for Europe. Atmospheric Environment 35, 6313-6325.

Brink, C., van Ierland, E., Hordijk, L. and Kroeze, C. (2005) Cost-effective emission abatement in agriculture in the presence of interrelations: cases for the Netherlands and Europe. Ecological Economics 53, 59-74.

Coggan, A., Whitten, S. M. and Bennett, J. (2010) Influences of transaction costs in environmental policy. Ecological Economics 69, 1777-1784.

Collier, U., Kennedy, D., Bellamy, O., Gault, A., Hafraoui, H., Meddings, N. and Srinivasan, K. (2013a) Reducing the UK's carbon footprint, Committee on Climate Change.

Collier, U., Kennedy, D., Kmietowicz, E., Bellamy, O., Gault, A., Hafraoui, H., Hill, J., Kazaglis, A., Meddings, N., Srinivasan, K. and Thillainathan, I. (2013b) Reducing the UK's carbon footprint and managing competitiveness risks, Committee on Climate Change.

19

Dalgaard, T., Hutchings, N., Dragosits, U., Olesen, J. E., Kjeldsen, C., Drouet, J. L. and Cellier, P. (2011) Effects of farm heterogeneity and methods for upscaling on modelled nitrogen losses in agricultural landscapes. Environmental Pollution 159, 3183-3192.

de Bruin, K., Dellink, R. B., Ruijs, A., Bolwidt, L., van Buuren, A., Graveland, J., de Groot, R. S., Kuikman, P. J., Reinhard, S., Roetter, R. P., Tassone, V. C., Verhagen, A. and van Ierland, E. C. (2009) Adapting to climate change in the Netherlands: an inventory of climate adaptation options and ranking of alternatives. Climatic Change 95, 23-45.

De Cara, S., Houze, M. and Jayet, P. A. (2005) Methane and nitrous oxide emissions from agriculture in the EU: A spatial assessment of sources and abatement costs. Environmental & Resource Economics 32, 551-583.

De Cara, S. and Jayet, P. A. (2000) Emissions of greenhouse gases from agriculture: The heterogeneity of abatement costs in France. European Review of Agricultural Economics 27, 281-303.

DeAngelo, B. J., de la Chesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C. (2006) Methane and nitrous oxide mitigation in agriculture. Energy Journal 27, 89-108.

DECC (2009) Carbon Valuation in UK Policy Appraisal: A Revised Approach, Climate Change Economics, Department of Energy and Climate Change (DECC), London.

Dominguez, I. P., Britz, W. and Holm-Muller, K. (2009) Trading schemes for greenhouse gas emissions from European agriculture: A comparative analysis based on different implementation options. Review of Agricultural and Environmental Studies - Revue d'Etudes en Agriculture et Environnement 90, 287-308.

Ducos, G., Dupraz, P. and Bonnieux, F. (2009) Agri-environment contract adoption under fixed and variable compliance costs. Journal of Environmental Planning and Management 52, 669-687.

European Environment Agency (2014) Annual European Union greenhouse gas inventory 1990-2012 and inventory report 2014, Report No EEA Technical report No 9/2014, European Environment Agency, Copenhagen.

Feliciano, D., Hunter, C., Slee, B. and Smith, P. (2014) Climate change mitigation options in the rural land use sector: Stakeholders' perspectives on barriers, enablers and the role of policy in North East Scotland. Environmental Science & Policy 44, 26-38.

Frankhauser, S. and Tol, R. S. (1996) Climate change costs: Recent advancements in the economic assessment. Energy Policy 24, 665-673.

Gielen, D. and Changhong, C. (2001) The CO_2 emission reduction benefits of Chinese energy policies and environmental policies: A case study for Shanghai, period 1995–2020. Ecological Economics 39, 257-270.

Glenk, K. and Colombo, S. (2011) Designing policies to mitigate the agricultural contribution to climate change: an assessment of soil based carbon sequestration and its ancillary effects. Climatic Change 105, 43-66.

Golub, A., Hertel, T., Lee, H. L., Rose, S. and Sohngen, B. (2009) The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. Resource and Energy Economics 31, 299-319.

Grijalva, T., Lusk, J. and Shaw, W. D. (2014) Discounting the distant future: An experimental investigation. Environ Resource Econ 59, 39-63.

Hallegatte, S., Shah, A., Lempert, R., Brown, C. and Gill, S. (2012) Investment Decision Making under Deep Uncertainty — Application to Climate Change, Report No WPS6193, The World Bank Sustainable Development Network.

IPCC Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (ed) (2006) 2006 IPCC guidelines for national greenhouse gas inventories, Prepared by the National Greenhouse Gas Inventories Programme, Volume 4: Agriculture, forestry and other land use, Institute for Global Environmental Strategies (IGES), Japan.

IPCC Stocker, T. F, Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (ed) (2013) Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kasterine, A. and Vanzetti, D. (2010) The effectiveness, efficiency and equity of market based and voluntary measures to mitigate greenhouse gas emissions from the agri-food sector. Trade and Environment Review 2010, United Nations Conference on Trade and Development (UNCTAD), Geneva,

Kesicki, F. and Ekins, P. (2012) Marginal abatement cost curves: a call for caution. Climate Policy 12, 219-236.

Kesicki, F. and Strachan, N. (2011) Marginal abatement cost (MAC) curves: confronting theory and practice. Environmental Science & Policy 14, 1195-1204.

Konidari, P. and Mavrakis, D. (2007) A multi-criteria evaluation method for climate change mitigation policy instruments. Energy Policy 35, 6235-6257.

Krutilla, K. (2011) Transaction costs and environmental policy: An assessment framework and literature review. International Review of Environmental & Resource Economics 4, 261-354.

Lempert, R. and Schlesinger, M. (2000) Robust Strategies for Abating Climate Change. Climatic Change 45, 387-401.

Lengers, B. and Britz, W. (2012) The choice of emission indicators in environmental policy design: an analysis of GHG abatement in different dairy farms based on a bio-economic model approach. Review of Agricultural and Environmental Studies - Revue d'Etudes en Agriculture et Environnement 93, 117-144.

Lenzen, M., Moran, D., Kanemoto, K. and Geschke, A. (2013) Building Eora: A global multi-region input-output database at high country and sector resolution. Economic Systems Research 25, 20-49.

Linkov, I., Satterstrom, F. K., Kiker, G., Batchelor, C., Bridges, T. and Ferguson, E. (2006) From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications. Environment International 32, 1072-1093.

McCann, L., Colby, B., Easter, K. W., Kasterine, A. and Kuperan, K. V. (2005) Transaction cost measurement for evaluating environmental policies. Ecological Economics 52, 527-542.

Mettepenningen, E., Verspecht, A. and Van Huylenbroeck, G. (2009) Measuring private transaction costs of European agri-environmental schemes. Journal of Environmental Planning and Management 52, 649-667.

Moran, D., MacLeod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, R. M., Topp, C. F. E., Pajot, G., Matthews, R., Smith, P. and Moxey, A. (2011) Developing carbon budgets for UK agriculture, land-use, land-use change and forestry out to 2022. Climatic Change 105, 529-553.

Moran, D., MacLeod, M., Wall, E., Eory, V., Pajot, G., Matthews, R., McVittie, A., Barnes, A., Rees, R., Moxey, A., Williams, A. and Smith, P. (2008) UK marginal abatement cost curves for the agriculture and land use, land-use change and forestry sectors out to 2022, with qualitative analysis of options to 2050, Report No RMP4950, Committee on Climate Change, SAC.

Naucler, T. and Enkvist, P. A. (2009) Pathways to Low Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve, McKinsey & Company.

21

Nemet, G., Holloway, T. and Meier, P. (2010) Implications of incorporating air-quality co-benefits into climate change policymaking. Environmental Research Letters 5, 9.

Nordhaus, W. and Boyer, J. (1999) Warming the World - Economic Models of Global Warming, Internet Edition ed. MIT Press.

OECD (2008) Handbook on Constructing Composite Indicators, OECD.

Pannell, D. J., Marshall, G. R., Barr, N., Curtis, A., Vanclay, F. and Wilkinson, R. (2006) Understanding and promoting adoption of conservation practices by rural landholders. Aust. J. Exp. Agric. 46, 1407-1424.

Pape, D., Moffroid, K. and Thompson, V. (2008) Analysis of the potential and costs for greenhouse gas emission reductions within the New Zealand agricultural sector, ICF International, Ministry of Agriculture and Forestry.

Pearce, D. W. and Turner, R. K. (1989) Economics of natural resources and the environment. Johns Hopkins University Press Baltimore.

Pellerin, S., Bamiere, L., Angers, D., Beline, F., Benoit, M., Butault, J. P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Dureau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Henault, C., Jeuffroy, M. H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E. and Savini, I. (2013) How can French agriculture contribute to reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures, INRA.

Peterson, S. (2006) Uncertainty and economic analysis of climate change: A survey of approaches and findings. Environmental Modeling & Assessment 11, 1-17.

Pretty, J. N., Brett, C., Gee, D., Hine, R. E., Mason, C. F., Morison, J. I. L., Raven, H., Rayment, M. D. and van der Bijl, G. (2000) An assessment of the total external costs of UK agriculture. Agricultural Systems 65, 113-136.

Price, R., Thornton, S. and Nelson, S. (2007) The social cost of carbon and the shadow price of carbon: What they are, and how to use them in economic appraisal in the UK, Department for Environment, Food and Rural Affairs; Crown copyright, London.

Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, J., Jacoby, H., Kicklighter, D., Melillo, J., Stone, P., Sokolov, A. and Wang, C. (1999) Multi-gas assessment of the Kyoto Protocol. Nature 401, 549-555.

Schneider, U. A., Mccarl, B. A. and Schmid, E. (2007) Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Agricultural Systems 94, 128-140.

Schulte, R. P., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Lalor, S. T., Lanigan, G., O'Brien, D., Shalloo, L. and Thorne, F. Schulte, R. P. and Donnellan, T. (ed) (2012) A marginal abatement cost curve for Irish agriculture, Teagasc.

Smith, L. A. and Stern, N. (2011) Uncertainty in science and its role in climate policy. Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences 369, 4818-4841.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. and Sirotenko, O. (2007) Agriculture, In: edited by B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (ed) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Smith, P. (2011) Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learnt in the last 20-years? Glob. Change Biol. n/a.

22

Thomas, J., Thistlethwait, G., MacCarthy, J., Pearson, B., Murrels, T., Pang, Y., Passant, N., Webb, N., Connoly, C., Cardenas, L., Malcolm, H. and Thomson, A. (2011) Greenhouse Gas Inventories for England, Scotland, Wales and Northern Ireland: 1990 - 2009, Report No AEAT/ENV/R/3222 Issue 1, ED56403200/Issue 1, AEA.

Tol, R. S. J. (2005) The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. Energy Policy 33, 2064-2074.

van Vuuren, D. P., Weyant, J. and de la Chesnaye, F. (2006) Multi-gas scenarios to stabilize radiative forcing. Energy Economics 28, 102-120.

Vermont, B. and De Cara, S. (2010) How costly is mitigation of non-CO_2 greenhouse gas emissions from agriculture?: A meta-analysis. Ecological Economics 69, 1373-1386.

Vogt-Schilb, A. and Hallegatte, S. (2011) When Starting with the Most Expensive Option Makes Sense - Use and Misuse of Marginal Abatement Cost Curves, Report No Policy Research Working Paper 5803, The World Bank, Sustainable Development Network, Office of the Chief Economis.

Wagner, F., Amann, M., Borken-Kleefeld, J., Cofala, J., Hoglund-Isaksson, L., Purohit, P., Rafaj, P., Schopp, W. and Winiwarter, W. (2012) Sectoral marginal abatement cost curves: implications for mitigation pledges and air pollution co-benefits for Annex I countries. Sustain Sci 7, 169-184.

Westhoek, H., Lesschen, J. P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M. A. and Oenema, O. (2014) Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. Global Environmental Change.

Winiwarter, W. and Klimont, Z. (2011) The role of N-gases (N_2O, NO_x, NH_3) in cost-effective strategies to reduce greenhouse gas emissions and air pollution in Europe. Current Opinion in Environmental Sustainability 3, 438-445.

23