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Cost-Effectiveness of Greenhouse Gas Mitigation Measures for Agriculture

A LITERATURE REVIEW

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The publication of this document has been authorised by Ken Ash, Director of the Trade and Agriculture Directorate.

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Abstract

COST-EFFECTIVENESS OF GREENHOUSE GAS MITIGATION MEASURES FOR AGRICULTURE: A LITERATURE REVIEW

Michael MacLeod, Vera Eory,
Guillaume Gruère and Jussi Lankoski

This paper reviews the international literature on the cost-effectiveness of supply-side mitigation measures that can reduce the emissions intensity of agriculture while maintaining or increasing production. Sixty-five recent international studies of cost-effectiveness covering 181 individual activities are reviewed. Nine case studies of well covered mitigation measures, generally using a cost-engineering approach, illustrate significant differences in the cost-effectiveness of measures across countries and studies, in part due to contextual differences. Although caution needs to be exercised in comparing heterogeneous studies, the results suggest that measures based on fertiliser use efficiency, cattle breeding, and potentially improving energy efficiency in mobile machinery, are often considered highly cost-effective mitigation measures across countries. A preliminary overview of policy highlights the existence of a range of options to encourage the adoption of cost-effective measures, from information to incentive-based policies. Further analysis is needed to address remaining estimation challenges and to help determine how mitigation measures may be embedded into broader climate, agricultural and environmental policy frameworks.

Keywords*:* Agriculture and climate change, greenhouse gas mitigation, cost-effectiveness, marginal abatement cost, cost-engineering approach.

JEL: Q16, Q52, Q54, Q58.

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EXECUTIVE SUMMARY

Agricultural greenhouse gas (GHG) emissions represent a significant proportion of the OECD's total emissions. For the period 2008-10, on-farm agricultural GHG emissions (excluding on-farm energy use, land use change, or emissions arising pre and post-farm) accounted for 8% of the total OECD emissions reported to the United Nations Framework Convention on Climate Change.

Agriculture has a potential role to play in GHG mitigation, even as the agriculture sector is responding to an increased demand for food. Demand for the major food commodities is forecast to increase significantly between now and 2050; in this context, reducing global emissions should be pursued in parallel to agricultural production objectives. There are opportunities to reduce the emissions intensity (i.e. the emissions per unit of output) of OECD agriculture whilst simultaneously improving productivity. Depending on the rate of increase of productivity, this could even lead to an absolute emission reduction.

Significant improvements in the emissions intensity of OECD agricultural output have already been observed due to technical and policy changes. Available estimates show that, on average, OECD countries have reduced their agricultural emission intensity by approximately 2% annually between 2000 and 2010. This has been achieved through a combination of the uptake of improved technologies and farm management practices, and incentives to lower emissions supported by a range of policies and policy reforms introduced by individual OECD countries.

Going further on this path demands knowledge about the range of feasible agricultural mitigation options, and on whether they can be technically effective, economically efficient, and socially acceptable. In particular, the cost-effectiveness of agricultural mitigation practices, an aspect which is the subject of multiple studies, is often highly variable, being very dependent on location, weather, past and current farming practices, and therefore difficult to gauge and assess for policy purpose.

This paper reviews the international literature on the cost-effectiveness of supply-side mitigation measures that can reduce emissions intensity while maintaining or increasing production. It therefore does not analyse demand side options, focuses on agricultural mitigation practices rather than potential policy instruments (such as carbon tax or carbon trading), and especially considers practices that reduce emissions while maintaining or increasing production. It is not a meta-analysis in that it does not claim to assess the average cost-effectiveness of measures.

There is a large number of potential mitigation measures and significant variation in the estimates of their impact, which is partly due to the methods used to assess them. Different methodologies can be used to derive marginal abatement cost curves: (i) bottom up cost-engineering; (ii) micro-economic modelling, with exogenous prices; (iii) regional/sectoral supply-side equilibrium models. This study identifies and reviews 65 recent international studies of the cost-effectiveness of eight categories of agricultural mitigation measures, covering 181 individual activities. Nine case studies of well covered mitigation measures, generally using a cost-engineering approach, illustrate significant differences in cost-effectiveness of measures across countries and studies, in part due to contextual differences.

Although caution needs to be exercised in comparing heterogeneous studies, the results suggest that measures based on fertiliser use efficiency and cattle breeding, and potentially improving energy efficiency in mobile machinery, are considered highly cost-effective mitigation opportunities across countries.

Preliminary policy discussions highlight the existence of different options to encourage the adoption of cost-effective measures, from information to incentive-based policies. For the measures that have low (or negative) costs and high effectiveness it should be possible to encourage uptake using policies focused on providing education and information. For the measures that are likely to have positive or moderate costs, but would provide net benefits to society (i.e. where the cost of implementing the measure is less than the social cost of the emissions), an incentive-based policy approach might be justified. In that case, two main approaches may be considered: the use of sector-wide or broader economic instruments (e.g. tax or cap and trade), or voluntary payment based approaches promoting targeted mitigation measures, each approach having potential advantages and drawbacks.

Further analysis is needed to address remaining estimation challenges, and to help determine how mitigation measures may be embedded into broader climate, agricultural and environmental policy frameworks. Despite the growing body of evidence, a number of technical challenges remain in the measurement of cost-effectiveness, including: (a) predicting the cost effectiveness of different combinations of measures; (b) accounting for leakages or displacement effects that move emissions from one place to another; (c) accounting for variability and uncertainty in cost-effectiveness; and (d) understanding why farmers are sometimes reluctant to adopt apparent “win-win” mitigation measures. Comprehensive analysis would also be needed to assess the costs and benefits of the different policy instruments for addressing GHG emission reduction in agriculture.

1. Mitigating greenhouse gas emissions in agriculture: A focus on supply-side emissions intensity improvement

Agricultural greenhouse gas (GHG) emissions represent a significant proportion of the OECD's total emissions. For the period 2008-10, agriculture (excluding energy use and land use change) accounted for 8% of the total OECD emissions reported to the United Nations Framework Convention on Climate Change (UNFCCC) (OECD, 2013; see Figure 8 in Annex A).

As presented in Figure 1, the major GHGs associated with agricultural production are:

- CH_4 arising mainly from the anaerobic decomposition of organic matter during enteric fermentation and manure management, but also from paddy rice cultivation;

- N_2O arising from the microbial transformation of N in soils and manures – during the application of manure and synthetic fertiliser to land and via urine and dung deposited by grazing animals; and

- CO_2 arising from (a) energy use pre-farm, on-farm and post-farm and (b) from changes in above and below ground carbon stocks induced by land use and land use change.

Within the OECD, annual on-farm CH_4 and N_2O emissions accounted for 1,183 $MtCO_2e$ in 2008-10 (OECD, 2013: p. 144). Each of these two gases accounted for half of the total that year. At the same time, contributions of agriculture to total national emissions varied considerably between countries, ranging from 2% in Japan to 46% in New Zealand (see detailed country estimates and trends in Annex A). It should be noted that these totals do not include CO_2 emissions arising from fuel combustion on-farm (e.g. for field operations), land use change on farm, or any emissions that occur off-farm, such as those arising from the production of inputs such as feed, energy and fertiliser.

Given this contribution, a number of reports and initiatives have highlighted the potential role of agriculture in GHG mitigation (e.g. Smith et al., 2014). Demand for the major food commodities is forecast to increase significantly between now and 2050; in this context, there is therefore likely to be decreased scope for reducing global emissions by reducing OECD agricultural production overall.[1] Instead, there are opportunities to reduce the emissions intensity (i.e. the emissions per unit of output) of OECD agriculture whilst simultaneously improving productivity.

Over the decade 2000 to 2010 absolute OECD GHG emissions decreased at a rate of 0.4% *per annum* while agricultural production volume increased by 1.6% *per annum* (OECD, 2013- see Annex A for emissions per country),[2] resulting in annual reductions of 1.97% in the emissions intensity[3] of OECD agricultural output. Such decoupling of production from negative environmental externalities is at the core of the objectives of green growth in agriculture (OECD, 2014). By reducing their emissions while increasing average agricultural productivity and value added, as shown in Figure 2, OECD countries contributing to what is defined as "absolute decoupling" in mitigation objectives (OECD, 2014).[4]

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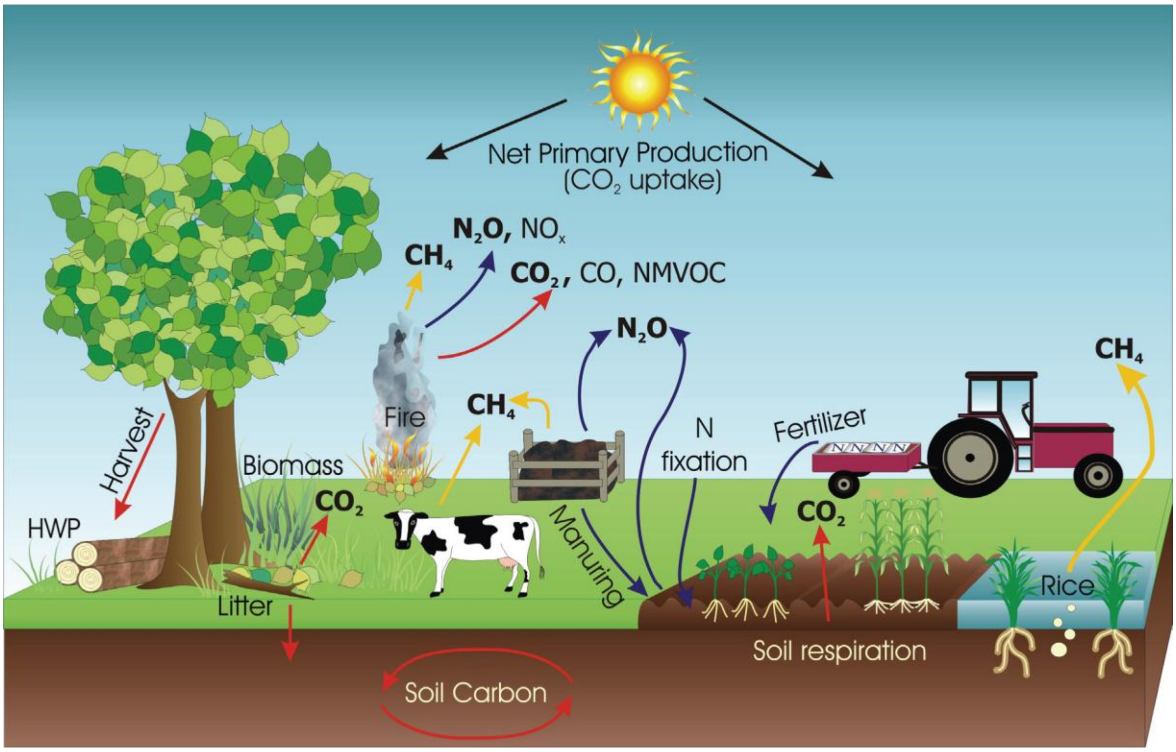
[1] Although opportunities may exist to improve efficiency by shifting current production either between OECD countries or from OECD countries to non-OECD countries which may have climatic or soil conditions more suited to more efficient agricultural production.

[2] See OECD (2013):57 for information on production indices.

[3] Emission intensity is defined as emission per output.

[4] Decoupling is said to be absolute when the economic variable is growing, while the environmental variable is stable or decreasing (OECD, 2014).

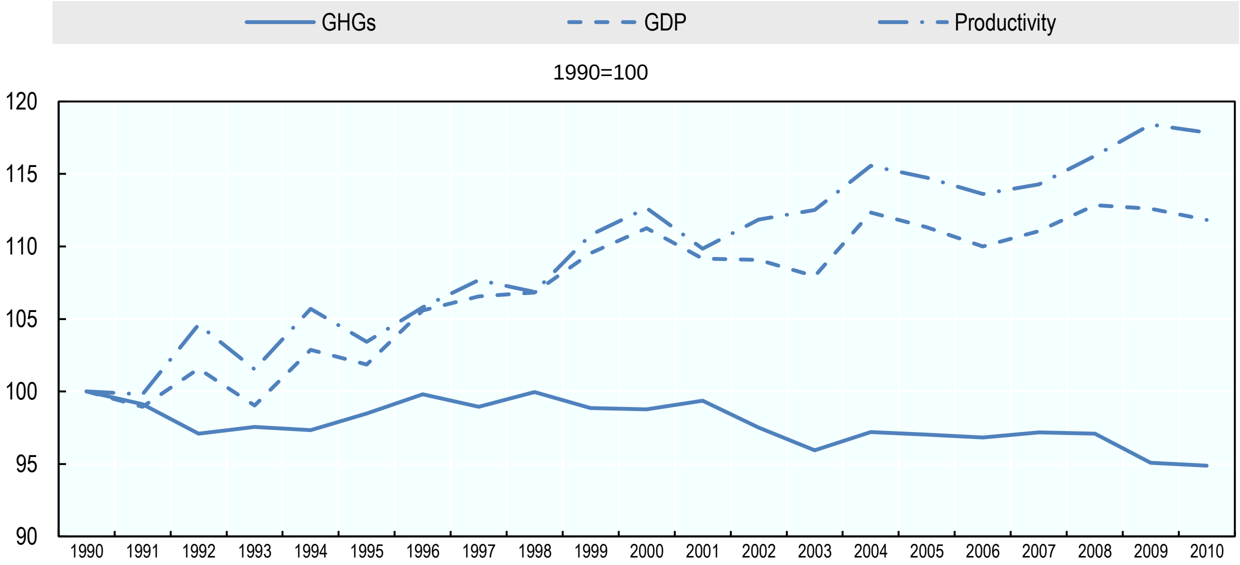
Figure 1. The main on-farm agricultural greenhouse gas emission sources, removals and processes in managed ecosystems



Note: Carbon sequestration is not explicitly represented but also plays a role in the GHG balance.

Source: IPCC (2006).

Figure 2. Trends in greenhouse gas emissions, agriculture GDP and productivity in OECD countries (1990-2010)



Note: Excluding LULUCF (land use, land use-change and forestry). *Source*: OECD (2014) based on UNFCCC Greenhouse Gas Inventory Data, http://unfccc.int/ghg_data/items/3800.php; FAO, FAOSTAT (database), http://faostat.fao.org/.

These results are largely attributed to the combination of the uptake of improved technologies and farm management practices, and incentives to lower emissions supported by a range of policies introduced by OECD countries. Public policies have played an important role in encouraging the uptake of mitigation practices in a number of countries. These policy instruments include, for instance, “providing farm advice to improve livestock feed efficiency and livestock growth rates to limit GHG emissions, and payments for biodigesters to reduce CH_4 emissions and replace highly emitting sources of energy” (OECD, 2013:149). As illustration, Box 1 describes some of the efforts undertaken in Ireland.

Box 1. Mitigating emissions in a ruminant agriculture: The case of Ireland

In Ireland, agriculture remains the single largest contributor to overall emissions at 31.1% (excluding energy use and land use change) of the total national emissions, reflecting the importance of agriculture to the Irish economy (contributing approximately EUR 10bn or 11% of total exports) and the dominance of ruminant agriculture on outdoor pasture based systems.

Because of this emissions profile there has been a substantial amount of work carried out on the analysis of potential mitigation options for the sector. Emissions from Irish agriculture reached a peak in 1998 and have been reducing steadily to 2011, through a number of measures, including Common Agricultural Policy reforms, participation in agri-environment and organic schemes, supports for manure management in line with the EU Nitrates Directive, supports for afforestation and through development of renewable energy resources. While emissions from Agriculture rose slightly in 2012 and 2013, they remained 7.3% below their 1990 level.

Irish agriculture has one of the lowest carbon-footprints internationally. In 2011 Ireland had the lowest cow milk emissions (1 kg per kg of product), the lowest emissions per kg of pork (4.8 kg/kg) in the European Union (Leip et al., 2010). Its emissions per kg of beef (18.4 kg/kg) were also under the EU Average 22.2 kg/kg. Emissions intensity per calorie of food output in 2013 is reduced approximately 14% relative to 2005 and early estimates project that under a business-as-usual 2030 scenario emission intensity will be a quarter below the emission intensity in 2005. Early estimates of agricultural emissions with additional measures are about 35% below 2005 emissions intensity levels.

Schulte and Donnellan (2012) have identified 1.1 Mt CO_2 abatement potential by 2020 and Schulte et al. (2014) proposing on a vision of carbon neutrality have been key to informing this discussion. Their report concludes that greater carbon efficiencies can be achieved in the agricultural sector. Substantial progress has been made in the farming and agrifood sector in reducing emissions through better farming techniques and improved animal husbandry. The substantial level of investment in innovation, research and development in farming and the agrifood sector in the period from 2005 to 2012 has assisted considerably in the development of new techniques. It has also helped to progress the significant work being done in farming and processing so that they operate in a smarter and more environmentally friendly manner.

Source: Note from the OECD Irish delegation, based on Leip, A. et al. (2010), “Evaluation of the livestock sector’s contribution to the EU greenhouse gas emissions (GGELS), European Commission Joint Research Centre, Ispra, Italy. http://ec.europa.eu/agriculture/analysis/external/livestock-gas/full_text_en.pdf; Schulte, R. and T. Donnellan (2012),” A Marginal Abatement Cost Curve for Irish Agriculture”, Teagasc http://www.teagasc.ie/publications/2012/1186/1186_Marginal_Abatement_Cost_Curve_for_Irish_Agriculture.pdf; Schulte, R.P.O., et al. (2013),”Carbon Neutrality as a horizon point for Irish Agriculture: a qualitative appraisal of potential pathways to 2050”, Teagasc, Dublin. http://www.teagasc.ie/publications/2013/3002/CarbonNeutrality.pdf.

Going further on this path requires knowledge about the range of possible agricultural mitigation options, their feasibility, and identifying those that are technically effective, economically efficient, and socially acceptable. In particular, the cost-effectiveness of agricultural mitigation practices is often highly variable, being very dependent on location, weather, past and current farming practices, and therefore difficult to gauge and assess for policy purpose.

The purpose of this report is to synthesize and analyse the growing evidence base on the cost-effectiveness (CE) of agricultural greenhouse gas (GHG) mitigation practices, with the view to inform the policy debate. It seeks to do this by reviewing the international literature and explaining key trends and concepts, and discussing a few preliminary policy implications and questions.

The study is however subject to several significant caveats. First it focuses primarily on cost-effectiveness, and therefore refrains from looking at other criteria, such as ancillary benefits and costs or private transaction costs, mostly because these other criteria remain largely unexplored (as explained in Section 2). They would warrant more empirical estimations. Second it is not a meta-analysis and does not seek to evaluate the comprehensive average CE of measures or to recommend the use of specific measures or policies. Instead, it aims at providing an overview of catalogued published studies with available estimates.

Third, the main focus in this paper is on mitigation *measure*s that can reduce *emissions intensity* while *maintaining or increasing production*, so that climate change and productivity improvement can be pursued simultaneously. These three scoping conditions are further explained below.

- The term mitigation can have several meanings and is often used to refer to a reduction in *total emissions*, usually expressed in terms of the change in total GHG emitted by a specified activity within a defined region and relative to a specified reference year, e.g. "Since 1990, emissions from agriculture and related land use (in Scotland) decreased by 4.2 $MtCO_2e$" (Scottish Government, 2013a: 2). However, in this report, mitigation refers to a reduction in the *emissions intensity*, i.e. the amount of GHG emitted per unit of output or input, for example the $kgCO_2e/kg$ product or $kgCO_2e/ha/year$ (see MacLeod et al., 2014, for a summary of measures of emissions intensity for food and drink products).[5]
- A distinction is made between mitigation *measures* (which are the activities undertaken on-farm to reduce emissions, e.g. planting cover crops or reducing N application) and *policies* (which refer to public policy instruments that can be used to encourage the uptake of a measure, e.g. providing information or incentives).
- The report focuses on measures targeting existing production practices. Global demand for food is forecast to increase significantly over the next 30 years (see Alexandratos and Bruinsma, 2012). This means that reducing agricultural production within the OECD would likely lead to compensatory increases in production outside the OECD. Given that OECD countries produce many of these commodities with lower emissions intensity than non-OECD countries (see Gerber et al., 2013, MacLeod et al., 2013; Opio et al., 2013), decreasing their production within the OECD might lead to a net increase in global emissions, ceteris paribus.[6]

Fourth, this paper focuses on supply-side mitigation measures, induced by reducing the quantity of GHGs emitted per unit of output, or by increasing the removal and storage of GHGs. Demand-side measures, which seek to achieve mitigation by changing what people consume and how they consume it, such as via improving efficiency (e.g. through the reduction of domestic food waste) or the substitution of certain products with lower emission intensity alternatives (for example, replacing beef with chicken meat, steel with wood or mineral diesel with biodiesel), are not included. However their absence does not imply a lack of potential. Demand-side measures provide scope for additional mitigation but would merit a separate study, given their fundamental differences to supply-side measures in terms of the policy approaches and quantification of their CE.[7]

Lastly, on the methodological side, this review focuses on cost-effectiveness as a criterion to assess practices, but alternative measures exist. McCarl and Schneider (2001) and McCarl and Sands (2007) distinguish between technical, economic and competitive (economic) mitigation potentials of alternative mitigation strategies. The technical potential refers to the maximum physical mitigation potential of a given mitigation strategy, while the economic potential takes into account (opportunity) costs of the given mitigation strategy. The technical potential is the upper bound of the economic potential. For example, Lewandrowski et al. (2004) showed that the economic potential to sequester carbon by

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5. Both types of emission reductions induce less emission than if no action had been taken. This is not the case if the total GHG reduction is achieved by displacing production and GHG.

6. Although it is recognised that in some cases reducing production in some location (particularly on marginal land) can lead to a net mitigation, even when the emissions from the displaced production are taken into account

7. For further discussion of mitigation via demand management see Bajželj et al. (2014).

adopting conservation tillage on additional lands with the highest assumed carbon price was only 25% of the estimated technical potential. The competitive (economic) potential considers that a given mitigation option will compete with other mitigation strategies (e.g. conservation tillage, afforestation and biofuels) and that this will further reduce economic potential of the given single mitigation strategy. McCarl and Schneider (2001) show that at USD 100 per metric ton of carbon US agricultural soils technical, economic and competitive mitigation potentials are approximately 150, 90, 65 million metric tons of carbon equivalent, respectively.

The rest of the report is organized in five sections. Section 2 describes and discusses the methods used to quantify the CE of mitigation measures. Section 3 then reviews the scope of recent studies on CE of mitigation measures. A series of short case studies are provided in Section 4 to illustrate some of the technical difficulties that arise in quantifying mitigation cost-effectiveness. These case studies also examine some of the challenges associated with implementing GHG mitigations measures. In order to illustrate how CE can vary, the results for a separate subset of commonly studied mitigation measures are compared in Section 5. This section also discusses preliminary policy implications and is followed by a short concluding section.

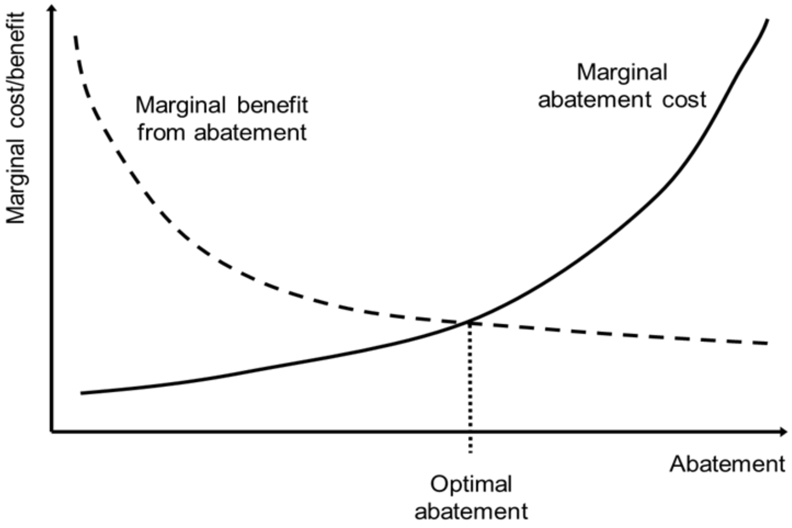
2. Three main approaches to assessing the costs of mitigation measures: Advantages and limitations

Marginal abatement cost curves

Increasing agricultural GHG mitigation efforts should strive to be achieved in ways that is cost-effective (i.e. focusing on measures that achieve the desired reduction at least cost) and socially efficient (i.e. reducing emissions up to the point at which the costs of mitigation are equal to the social benefits of reducing the emissions). A range of studies have attempted to quantify the cost-effectiveness of mitigation measures (although the full social costs are not usually included in these studies). This information is frequently depicted on a marginal abatement cost curve, or “MACC”, an assessment tool widely used in policy analysis. A MACC shows the cost of reducing pollution by one additional unit (expressed in CO_2 equivalent) and can be plotted against a curve showing the marginal benefit of reducing pollution to enable the identification the optimal level of pollution abatement (see Figure 3). In GHG mitigation studies, the MACCs derived from modelling are often smooth curves, while those based on bottom-up cost engineering approaches are more often represented as a series of discrete bars, each of which represents a mitigation measure (Figure 4). The width of each bar represents the reduction in GHG emissions, while the height of the bar shows the cost-effectiveness of the measure. The area under each bar is equal to the total cost of the measure. Box 2 provides an example of a comprehensive application of the MACC method to compare projected mitigation potentials across regions and sector.

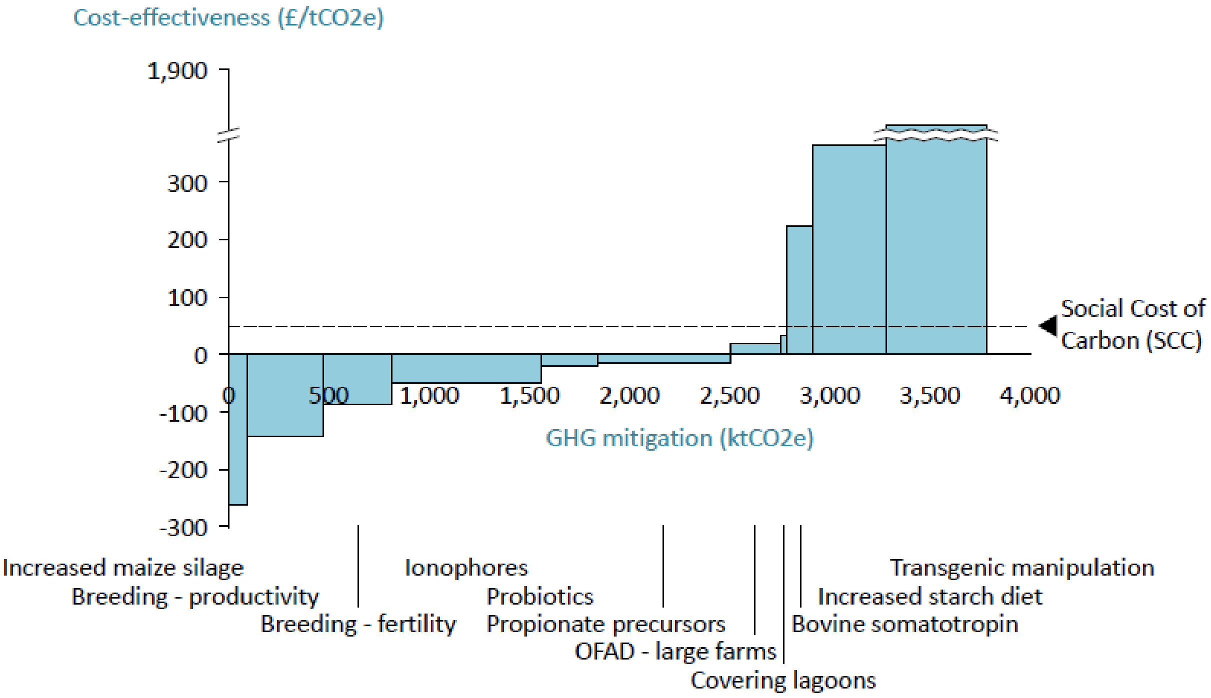
Figure 3. Marginal abatement costs and benefits

For a given technical measure, optimal pollution abatement occurs where the marginal cost of abatement equals the marginal benefit, i.e. where the two curves cross



Source: Pearce and Turner (1990).

Figure 4. Example of marginal abatement cost curve (MACC) for UK dairy mitigation measures



Note: OFAD: on-farm anaerobic digestion.

Methodologies used to develop MACCs

The marginal cost of abatement can be calculated in various ways. Vermont and De Cara (2010) divides MACCs into three main types based on the methodology used to derive the curves: (i) bottom up cost-engineering; (ii) micro-economic modelling, with exogenous prices; (iii) regional/sectoral supply-side equilibrium models.[8]

(i) Bottom-up cost-engineering

In this approach, information on the one-off and recurring costs of a range of mitigation measures and their effect on emissions is collected. These data are used to calculate (a) the average annual cost of each measure, (b) the amount of emissions reduced each year, and (c) the cost-effectiveness, i.e. the cost per unit of GHG mitigated. The results for each measure are then plotted, usually in order of increasing cost-effectiveness. Examples include the McKinsey marginal abatement cost curves (Naucler and Enkvist, 2009) and the illustration in Figure 4.

(ii) Micro-economic modelling, exogenous prices

While it is possible to consider some measures as stand-alone investments, for the most part agricultural measures need to be integrated into farm systems that operate under specific land, labour and capital constraints. If the farm is considered to be operating at some notional efficiency frontier then an additional measure can displace other productive activities, creating an opportunity cost. For example, purchasing a slurry tank cover may prevent a dairy farm from making other investments designed to increase milk yield. The true cost of implementing a measure should therefore include an estimate of this opportunity cost, which can be derived by farm scale economic modelling. An example for this approach is a spatial assessment of agricultural non-CO_2 mitigation costs in the EU (De Cara et al., 2005).

(iii) Regional/sectoral using supply-side equilibrium models

The third approach uses 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. Weyant et al. (2006) identify three distinct types of equilibrium models: multi-sector general equilibrium, aggregate general equilibrium, and market equilibrium. Examples of this approach are 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 depicting the European agriculture (Dominguez et al., 2009). These top-down approaches have the “ability to capture the intersectoral or international propagation mechanisms and feedback induced by a localised policy shock such as a taxation policy or the imposition of a standard in the agricultural or forestry sectors” but are very data demanding (Povellato et al., 2007).

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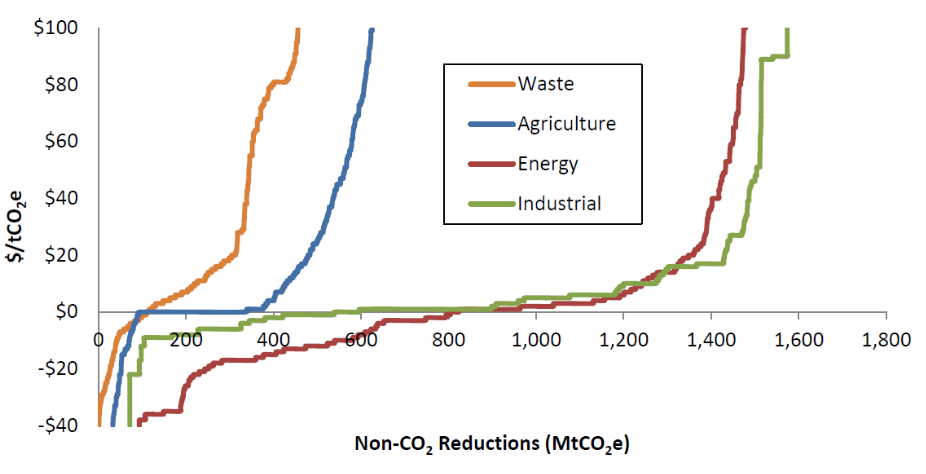
[8] The three approaches are however not independent: the latter two approaches may require information from the first approach.

Box 2. Using MACCs to analyse projected the cost-effectiveness of non-CO_2 GHG mitigation options across sectors and countries

USEPA (2013) conducted a broad investigation of current and projected non-CO_2 emission sources (CH_4, N_2O and other gases) and the cost-effectiveness of mitigation measures by 2030 at the global level. Using a bottom-up cost-engineering approach, the report derives comparable MACCs in specific countries and for four different sectors in 2010 and 2030.

Figure 5. Projected MACCs of non-CO_2 emissions for agriculture and three other sectors in 2030



Source: USEPA (2013).

The report shows that agriculture is and will remain the primary source of non-CO_2 emissions (representing 45% of total) in 2030. At the same time, agricultural GHG mitigation is not as cost-effective as efforts in the industrial and energy sectors at the global scale, but it is more cost-effective than efforts in the waste sector (Figure 5). For instance at a break-even price of $30/t$CO_2$e, agriculture's potential mitigation is estimated to be around 500MtCO_2e, compared to 332MtCO_2e for waste and over 1400MtCO_2e for the energy and industrial sectors.

The agriculture section of the report then analyses more specifically three main sources of GHG emissions; livestock (21% of projected 2030 non-CO_2 emissions), rice (6%), and other cropland (4%). In the case of livestock, improved feed conversion efficiency, feed supplements and anaerobic digesters are identified as the main low cost options, but the total technical reduction is only 10% of total livestock emissions in 2030. The analysis finds that 26% of non-CO_2 emissions from rice cultivation can be reduced via technical measures, and identify conversion to dryland production as the option with the largest potential. Lastly, no-till and reduced fertilizer application provides 80% of the mitigation technical potential for other crop land (which amounts to 26% of total cropland emissions of non-CO_2 in 2030).Unlike in other cases, global MACC for croplands are also found to be shifting towards the left between 2010 and 2030, showing a lower CE potential over time, as the soil becomes saturated with C.

Source: USEPA (2013), "Global Mitigation of Non-CO_2 Greenhouse Gases: 2010-2030", EPA-430-R-13-011, US EPA, Washington, D.C.

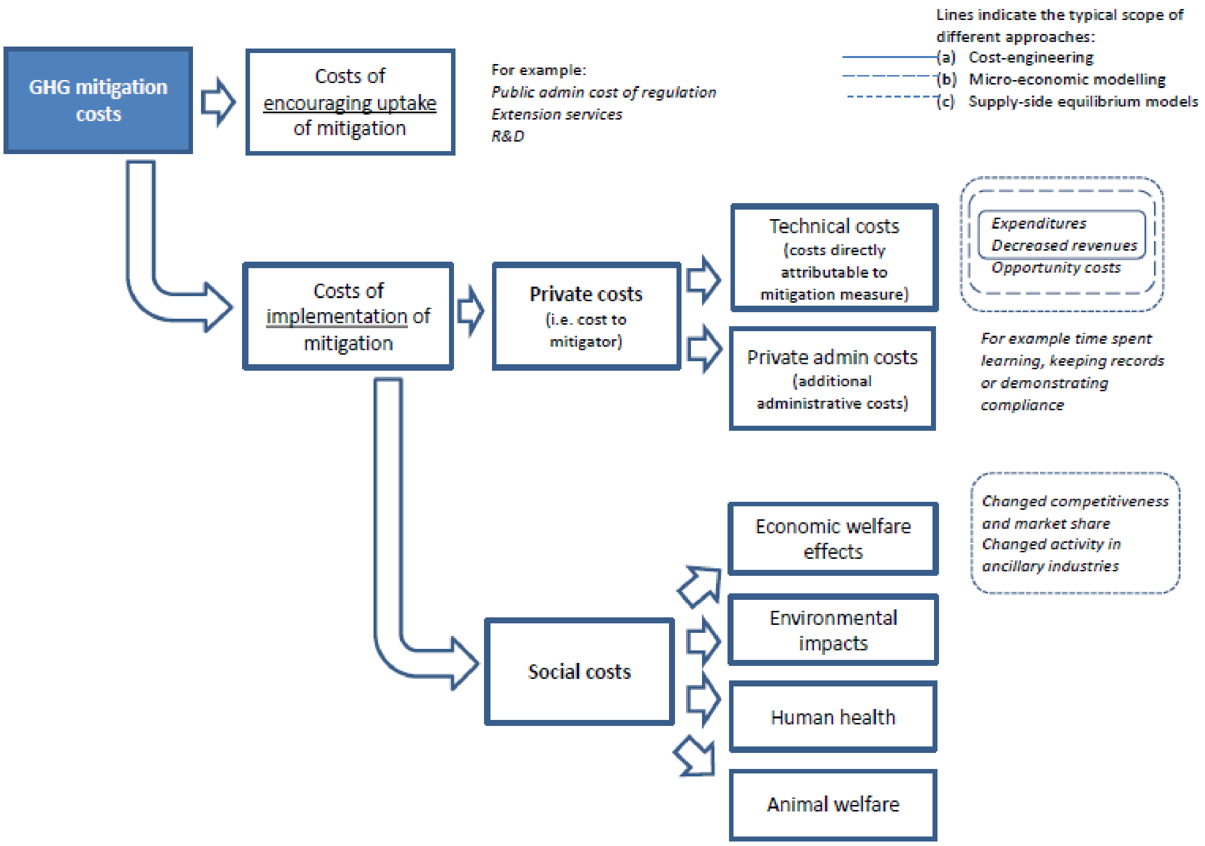
Choice of method and application

The three methods do not account for the same types of costs, and none of the three covers all mitigation costs. Different types of costs can arise from the use of mitigation measures, as shown in Figure 6. Some mitigation measures can induce positive or negative costs (i.e. benefits). For example, it has been argued that environmental regulation can reduce or enhance competitiveness (see MacLeod et al., 2009, p20). Likewise, mitigation measures may have multiple environmental co-impacts, leading to a resulting net cost or benefit. Figure 6 indicates the extent to which the different approaches can capture different types of costs. This categorisation is, however, somewhat tentative, and does not imply that these methods fully capture all the costs within the presented boundaries. For example, while supply-side equilibrium models can capture expenditures and revenue changes, they are not necessarily best suited to this task; rather their strength lies in capturing economic welfare effects. Most importantly, regardless of which method is used, some costs (or benefits) will be excluded, and the results should be interpreted with this in mind.

Acknowledging these limitations, the choice of method depends on the aims of the analysis being undertaken. In simplistic terms, equilibrium models are good at capturing economy-wide interactions and are useful if one is interested in questions such as what the effects of a policy to reduce agricultural emissions might have on supply and demand. Micro-economic modelling can provide insights into questions such as how uptake of a particular measure might affect the financial performance of different farm types or sizes. The bottom-up engineering approaches tend to be better suited to developing an overview of technical mitigation measures options, but they rarely capture the opportunity costs. Ultimately, if one is interested in the social costs of mitigation then social cost-benefit analysis may be more suitable than cost-effectiveness analysis.

Empirical research suggests that the choice of method may affect the cost estimates for given measures, especially at low emission prices, even if none of the methods can be considered more accurate than the others. Vermont and de Cara (2010) use a meta-analysis to show that the mitigation costs coming out of equilibrium models are consistently lower than those coming out of supply side microeconomic models. Estimates derived from the latter models are also higher than those induced from engineering approaches at low emission prices. Further discussion of the relative merits of different approaches via their effects on results is provided in Box 3 (see also Povellato et al., 2007 and Kesicki and Strachan, 2011). The main implication of such results is the need to be cautious with the interpretation of absolute values of estimates. It also encourages the use of the same method for cost-effectiveness comparison across measures.

Figure 6. Classification of costs arising from mitigation



Box 3. Implications of the different modelling approaches: results from a meta-analysis

Vermont and Cara (2010) discuss the implications of the chosen modelling approach on the estimated abatement potential and abatement costs. Supply side microeconomic models with exogenous prices provide detailed description of production feasibility set, are highly disaggregated, and the abatement costs derived from these models closely resemble the standard definition of marginal abatement cost. Equilibrium models (partial or general) include demand for agricultural products and thus endogenous prices, which means that the mitigation policy has two effects: (i) a direct effect through changes in supply and (ii) an indirect effect through changes in equilibrium prices (and thus affect opportunity costs of mitigation policy). High degree of flexibility in resource allocation in equilibrium models may imply lower abatement costs than those given by supply side models; however, price effects from markets may increase opportunity costs of mitigation and thus abatement cost estimates provided by equilibrium models.

Vermont et de Cara (2010) then lead a meta-regression analysis of non-CO_2 mitigation costs in agriculture on the basis of 21 studies. Their results show that supply side microeconomic models consistently report higher abatement costs for a given reduction of emissions than equilibrium models (or alternatively lower abatement rate for given price of emissions). Moreover, at low emission prices (EUR 10/tCO_2-eq) the abatement rates of supply side micro-economic models are 60% lower than those given by engineering approaches. This difference declines with higher emission prices and implies that the most abatement potential reported in engineering approaches comes from practices with low or even negative costs.

Source: Adapted from Vermont and de Cara (2010), “How costly is mitigation of non-CO_2 greenhouse gas emissions from agriculture?: A meta-analysis”, *Ecological Economics* 69, 1373-1386.

In order to calculate the width of the bars in a MACC —i.e. the abatement potential or reduction in GHG over a given time period— two variables are needed: the measure’s abatement rate (i.e. the change in the quantity of GHG and/or the change in yield per hectare or animal), and the additional area or number of animals (over and above the present) that the measure could be applied to in the given period.

Some measures can in theory be applied to a large proportion of the available land. However, the extent to which mitigation measures are adopted in practice depends on the specifics of the measure and the policy framework. MACCs can be constructed to reflect abatement potentials in terms of these different levels of adoption. For example, MacLeod et al. (2010) distinguish between four potential abatement scenarios: maximum technical; high feasible; central feasible; low feasible. Maximum technical abatement potential is the amount by which it is possible to reduce GHG emissions if everyone who is technically able to implement a measure does so as far as possible. The high, medium and low reflect the abatement potential under different policy scenarios, and uptake rates for these were estimated based on a review of uptake/compliance with existing policies. One of the challenges in estimating abatement potentials is determining the extent to which any uptake is additional to the business-as usual case. Many farm practices are not routinely recorded, which can make accurate determination of baselines (and therefore measurement of progress) problematic.

Limitations of MACCs

While MACCs are a useful way of conveying information, they also have a range of limitations and need to be interpreted with some care. Key limitations are outlined below (for further discussion of the limitations of MACCs see Eory, 2014; Kesicki and Ekins, 2012; and Vermont and De Cara, 2010).

a) Scope

The scope of the analysis can be variable and/or imprecisely defined in terms of the system boundary and the emissions and costs categories included within it. This can lead to exclusion of potential mitigation opportunities, biased cost estimates and biased estimates of mitigation potentials. The costs included depend partly on which method is used (Figure 6). Some costs are more difficult to quantify and are therefore frequently excluded from CE calculations. These can include some private costs (such as increased exposure to risk or increased administrative burden), social costs (such as ancillary environmental impacts) or the costs incurred in facilitating and encouraging uptake of mitigation. Displacement of emissions to categories and/or locations outside the scope of the analysis can lead to overestimation of mitigation potentials. These effects can be identified and quantified through the use of life-cycle approaches.

b) Heterogeneity and uncertainty

MACCs are essentially static and tend to provide a high-level snapshot of the average or typical performance of a set of mitigation measures at a point in time. In reality, the cost-effectiveness and abatement rates are likely to vary spatially and temporally. MACCs for representative farm types, farm sizes or regions may be constructed to better reflect the heterogeneity (see, for example, Dequiedt and Moran 2015).

Uncertainties associated with uptake levels, abatement rates and costs arise as a result of both natural variability and our limited knowledge about the underlying biophysical and social processes. Where possible, these uncertainties should be quantified and included in MACCs. Those that cannot be quantified (e.g. future policies are difficult to predict) should at least be stated explicitly.

c) Interactions

Synergies between mitigation measures (and potential incompatibilities and path dependencies) and their effects on abatement and cost are difficult to communicate with MACCs. Agricultural GHG emissions are characterised by interactions between various emission sources —such as chemical fertiliser and manure application, land allocation between alternative crops with different emission intensities— and alternative modelling approaches differ regarding the treatment of these interactions. Supply-side microeconomic models contain interactions at the farm level (e.g. through livestock feeding constraints), while equilibrium models capture interactions through price-effects (e.g. through price induced changes in livestock feeding regimes and land use). Engineering approaches can model interactions, but do so in a less transparent way (Vermont and Cara, 2010). Moreover, the abatement potential of given mitigation practice is not independent of the level of other mitigation practices, since alternative practices may have competing or complementary relations.

Hence, simultaneous consideration of abatement practices is needed rather than independent assessment (Schneider and McCarl, 2006). Pellerin et al. (2013) takes into account the interactions within and between selected abatement measures and show that cumulative abatement potential falls by 8% or 18%, depending on the calculation method adopted.

d) Discount rates

Choice of discount rate can lead to systematic bias in cost estimates that favours or penalises measures with particular cost and mitigation profiles. A range of discount rates should be used to create contrasting MACCs wherever possible.

e) Including ancillary costs and benefits in CE analysis

MACCs are designed to present the CE of reducing one specific type of externality (e.g. GHG emissions). 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 focus on one externality excludes ancillary effects (on, for example, water quality or biodiversity) from the analysis, which can significantly change the results (Glenk and Colombo, 2011, Nemet et al., 2010).

Box 4. MACCs with multiple pollutants

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. 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 way 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 GHG: the common metric is CO_2-equivalents; non-CO_2 gases usually being converted by using global warming potential (GWP) values.
- A second approach, used when no physical unit can be easily constructed for the integration of different pollutants, consists in constructing a composite indicator (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 (MCA) 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. MCA 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 ancillary 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.

Source : Amann, M., et al. (2011), "Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications", *Environmental Modelling & Software* 26; Anthony, S. et al. (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; de Bruin, K., Dellink, R. B., et al. (2009), "Adapting to climate change in the Netherlands: an inventory of climate adaptation options and ranking of alternatives", *Climatic Change* 95; Konidari, P. and Mavrakis, D. (2007), "A multi-criteria evaluation method for climate change mitigation policy instruments", *Energy Policy* 35; Linkov, I., et al. (2006), "From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications*", Environment International* 32; OECD (2008), *Handbook on Constructing Composite Indicators*; Pretty, J. N., et al.(2000), "An assessment of the total external costs of UK agriculture", *Agricultural Systems* 65; Schneider, U.A., et al.(2007), "Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry", *Agricultural Systems* 94; Winiwarter, W. and Klimont, Z. (2011),"The role of N-gases (N_2O, NOx, NH_3) in cost-effective strategies to reduce greenhouse gas emissions and air pollution in Europe", *Current Opinion in Environmental Sustainability* 3.

GHG mitigation measures can have a variety of ancillary effects (see Table 26 in Annex B), and failure to include these 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 (beyond climate change). That does not prevent the MACC approach from being well suited for high-priority issues, like climate change, where previously agreed pollution thresholds have to be achieved, or when the funding sources for the particular pollutant have already been agreed upon. Secondly, 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 affecting adaptation (e.g. OECD, 2014), the co-effects would make the GHG mitigation activity more or less desirable than indicated by a pure GHG CE metric.

To overcome these limitations, 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 MMs. Alternatively, techniques can be used to integrate multiple effects as illustrated in Box 4.

The main differences and caveats in approaches reviewed in this section should be kept in mind when delving into the results of the literature review and case studies of mitigation measures.

3. Breadth of the reviewed literature: 65 studies provide estimates of cost-effectiveness of up to 181 agricultural mitigation measures

The review sought to include all the recent studies available in English (primarily those published within the last ten years) that assess the cost-effectiveness of multiple mitigation measures (i.e. studies focussing on only one measure were not included). The studies were identified using a regularly updated database of mitigation studies maintained by Scotland's Rural College (SRUC) and augmented with literature suggested by the report's reviewers.

The review identified 181 separate mitigation measures, which were aggregated into 30 sub-categories and further organised into eight categories. The number of measures within each category and the number of times mitigation measures within each category were included in the studies reviewed are given in Table 1, with details on studies in Annex Table 27 and 28. Note that Table 27 only includes (a) studies that reported cost-effectiveness for specific mitigation measures (rather than for general categories of measures or policies), and (b) only counts measures that had their cost-effectiveness quantified in a study. For example, "Animal Health" is discussed as a potential mitigation measure in Schulte et al. (2012), but the cost-effectiveness is not quantified.

Table 1. Number of individual mitigation measures in each category, and the total number of times mitigation measures in each category were included in the studies reviewed

Category	Number of measures	Number of inclusions
Cropland management	64	179
Grazing land management	16	34
Management of organic soils	1	2
Restoration of degraded lands	4	5
Livestock management	49	120
Housing and manure	24	67
Land use change	7	7
Energy efficiency	16	23

Most of the studies in Table 1 focus on non-CO_2 mitigation measures in OECD countries. While there are some global studies, few focus specifically on developing countries, which are where most growth in agricultural emissions is likely to occur. Most studies cover measures to mitigate N_2O and CH_4 rather than CO_2 emissions (either arising from land use change or from energy use), due to their respective coverage and importance in total GHG emissions. This is a weakness in the literature, given that on-farm energy consumption can represent a relatively significant proportion of emissions in some agricultural subsectors (vineyard cultivation), or in regions with significant groundwater-irrigated areas.

Although methods are not always fully and clearly stated, bottom-up cost engineering approaches are the most common. Beyond the limitations of this approach discussed in section 2, using this approach opens the possibility of finding negative cost measures (e.g. see Figure 4), that would not be derivable via supply-side or equilibrium modelling approaches. While these negative costs could be considered as modelling artefact, they do not impede on helping to assess the overall cost-effectiveness of measures, especially when ranking similarly evaluated measures.

In terms of the system boundaries, the majority of studies focus on emissions arising on-farm; relatively few studies use life cycle analysis (LCA) to quantify emissions.[9] On-farm actions (such as changing feed or fertiliser use) can have effects on the pre and post-farm parts of the supply chain, but this remains an area with only few comparable cost-effectiveness estimations.

Finally, the estimates of CE are based on the current state of knowledge, however research, technology and development (RTD) should be able to identify new mitigation options and extend the mitigation potential of existing options.[10] MacLeod et al. (2010c) identified a range of measures for which significant additional mitigation could be realised via RTD. The report also highlighted the need to understand the socio-economic issues such as the technical barriers to uptake of measures, consumer acceptability and how the benefits of measures can be demonstrated. There are several ongoing initiatives seeking to use RTD to reduce GHG emissions. For example, the Global Research Alliance on Agricultural Greenhouse Gases focuses on research efforts across the agricultural sub-sectors of paddy rice, cropping and livestock, and the cross-cutting themes of soil carbon and nitrogen cycling and inventories and measurement issues.[11]

4. Case studies of specific measures: A wide range of costs

To illustrate in more detail the scope of mitigation measures, this section details nine short case studies covering:

1. Cover crops
2. Precision nutrient application
3. Nitrification inhibitors
4. Land use change from grassland to forest
5. Fat supplementation in ruminant diets
6. Breeding to reduce enteric CH_4
7. Anaerobic digestion
8. Improving energy efficiency in mobile machinery
9. Use of biological N fixation in crop rotations and in grass mixes

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[9] For LCA approach, see e.g. Coderoni et al. (2015) who employ so-called carbon footprint to investigate the mitigation potential and costs of six livestock products in Italy.

[10] For example, the reduction of N2O emissions after biochar soil amendment has been recently reported in many studies. Cayuela et al. (2014) conducted a review and meta-analysis of laboratory and field experiments (261 experiments) and found that biochar reduces soil N2O emissions by 54%.

[11] See www.globalresearchalliance.org/.

The case studies were chosen to provide examples that cover the main agricultural emission sources within the OECD. Table 2 shows the main on-farm emissions sources targeted in the case studies. The case studies were also selected to achieve a balance between the different approaches to mitigation and to illustrate some key issues in assessing cost-effectiveness. Still, as shown in Table 2, some emissions sources that are relatively less important at an OECD-wide level, but can be highly significant within particular countries and regions, such as CH_4 from flooded rice cultivation in East Asia, are not covered. It should also be noted that the case studies focuses on measures with reported quantification on cost-effectiveness. Other measures, for which there is still limited evidence, may present significant potential for mitigation. As illustration, Box 5 presents two measures, in the process of being developed and used especially in France, which may provide mitigation opportunities and other benefits. Overall, the choice of case studies *does not* imply priority of these measures over other mitigation measures; instead, they have to be considered as illustrative examples.

Table 2. The main on-farm emissions sources targeted by the mitigation measures in the case studies

Case study	CH_4: enteric	CH_4: manure management	N_2O: manure management	N_2O: grazing	N_2O: soils	CH_4: rice	CO_2: fuel	CO_2: C stocks
Cover crops					x			x
Precision nutrient application					x			
Nitrification inhibitors				x	x			
Land use change								x
Fat supplementation in ruminant diets	x							
Breeding to reduce enteric CH_4	x							
Anaerobic digestion		x						
Improving energy efficiency machinery							x	
Use of biological N fixation					x		x	

For each case study, the expected GHG emission reduction impact and costs are reviewed, other costs and benefits are considered, and the implementation issues their uptake may raise are discussed. The focus is on emission sources more directly amenable to OECD policy, i.e. emissions arising within the OECD countries, rather than emissions imported (e.g. arising from feed and fertiliser production outside the OECD). This follows conventional UNFCCC measurement methods, but the induced complex supply chain effects should be borne in mind.

Box 5. Examples of alternative mitigation measures in development

Increasing pastureland area and better management of grazing can increase carbon storage in soils (Soussana et al., 2007 and 2010; INRA, 2013). The storage capacity potential in pasture land depends on pedoclimatic conditions, but also on management approaches: land allocation decisions (the use of permanent pasture, or rotating temporary ones), pastureland management practices (e.g. duration of the temporary pasture land, number of cuttings), or the farm's production intensity (fertilisation and stocking density). Recent studies show that low intensity grazing increases carbon sequestration, while reducing GHG emissions from soil (N_2O) and from livestock (CH_4) (Soussana et al., 2010). Improved pasture management therefore induces 1) carbon sequestration, 2) reduced N2O emissions associated with effluent management, 3) decreased CO_2 emissions from fossil fuel combustion in field activities, and 4) a reduction of CH_4 animal emissions (direct emissions and indirect via effluents).

In practice, such better management consists in (INRA, 2013): extending the grazing period by about 20 days (Arrouays, 2002), increasing the duration of temporary pasture; ensuring a lower intensity of fertilizer application on permanent and temporary pastureland, and improving relatively less productive pastureland by augmenting the vegetal cover. If emission reductions from pastureland area increase and management improvements are relatively easy to measure, it is still challenging to estimate the reduction of the indirect emissions. Indirect effects are expected before and after the production stage. At the pre-production stage, the reduction in the use of animal feed (lower feed requirement and transportation) and potential associated indirect land use effect (deforestation) to produce soymeals likely create positive GHG emission effects. The manufacture and transportation of fertilizers, and the fuel used also contribute to reductions at this stage. At the post-production stage, indirect positive effects include a reduction of N_2O emissions associated with variations in potential nitrate run offs and NH_4 emissions. These two indirect GHG emission sources are modified by the evolution of fertilization practices and the management of effluents in pastureland.

The development of landscape elements and agro-ecological structures, including the use of hedgerows and agro-forestry practices, can help capture atmospheric CO_2 via an increase in carbon storage in soils' organic matter and perennial trees' biomass (INRA, 2013, Arrouays et al., 2002; Kumar and Nair, 2011). In addition to CO_2 capture, systems associating field crops and trees can also increase farmers' income. If the average crop yield is sometimes diminished, wood products valorisation, and the capacity of these systems to reduce yield losses in dry years— due to the adaptability they confer to the system (better water regulation, better nutrient absorption, sun protection- Verchot et al., 2007)—can improve farmers' overall income (Albercht and Kandji, 2003).

Source: Albrecht, A. and S.T. Kandji (2003), "Carbon sequestration in tropical agroforestry systems", Agriculture Ecosystems and Environment 99:15–27; Arrouays D., et al. (2002), « Contribution à la lutte contre l'effet de serre. Stocker du carbone dans les sols agricoles de France ?», Expertise scientifique collective, INRA, France ; INRA (2013), «Quelle contribution de l'agriculture française à la réduction des émissions de gaz à effet de serre ?», Expertise collective, INRA, France. http://institut.inra.fr/Missions/Eclairer-les-decisions/Etudes/Toutes-les-actualites/Etude-Reduction-des-GES-en-agriculture ; Kumar, B.M.; Nair, P.K.R., 2011. Sequestration potential of agroforestry systems: opportunities and challenges. Advances in Agroforestry, n°8. Springer Science Dordrecht: (http://library.uniteddiversity.coop/Permaculture/Agroforestry/Carbon_Sequestration_Potential_of_Agroforestry_Systems-Opportunities_and_Challenges.pdf Soussana, J.F. et al. (2007), "Full accounting of the greenhouse gas (CO_2, N_2O, CH_4) budget of nine European grassland sites", Agriculture, Ecosystems and Environment, 121, 121–134. Soussana, J.F. et al. (2010), "Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands", Animal, 4, 334-350; Verchot , L.V. et al. (2007), "Climate change: linking adaptation and mitigation through agroforestry", Mitigation and Adaptation Strategies for Global Change 12 (5): 901-918

4.1 Cover crops[12]

Introduction

A cover crop is a fast growing crop grown at the same time as, or between plantings of, a main crop. It provides a variety of benefits, notably: reduced soil erosion, improved soil structure and moisture retention, N fixation, weed suppression and insect habitat provision (Lu et al., 2000). Among these, catch crops are a type of cover crop grown for the purpose of absorbing surplus N remaining after harvest of the main crop, and thereby reducing the rate at which N is lost from the soil. Another potential cover crop is the planting of permanent or temporary green cover in orchards and vineyards.

Cover crops can mitigate GHG emissions in four main ways: by increasing soil organic carbon content, by decreasing soil carbon loss due to erosion during the fallow period; via a reduction in N leaching (and subsequent N_2O emissions) and by reducing the amount of N that needs to be applied to the following crop (reducing synthetic fertiliser use).

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[12] This case study is partly based on Frelih-Larsen et al. (2014).

Expected impacts on GHG emissions

The main on-farm mitigation effect of cover crops is via enhanced soil carbon storage (Table 3). The N_2O emissions reduction effect through the uptake of nitrate and ammonium can be uncertain. For this reason, some studies (Pellerin et al., 2013: p. 44) excluded it from the mitigation calculations (French MACC). Small reductions in CO_2 can also arise if the cover crops lead to a reduction in the amount of synthetic fertiliser applied, but these are likely to be offset by the small increase in diesel used for cultivation of the cover crop as shown in Table 3.

Table 3. Abatement rates for cover crops sown during the fallow period for arable rotations

Mitigation effect	Abatement rate	Source	Location
Increased soil C	0.874+/- 0.393 tCO_2e/ha/yr	Pellerin et al. (2013) (based on Justes et al. (2012)	France
	1tCO_2e/ha/yr	Schulte et al. (2012)	Ireland
	“small, but significant increase in SOC” (soil organic carbon)	Kirk et al. (2012)	United Kingdom
	1.75tCO_2e/ha/yr	Posthumus et al. (2013)	United Kingdom
Reduce direct and indirect N>N_2O Emission Factors	Highly variable	Pellerin et al. (2013)	France
	0.49tCO_2e/ha/yr	Schulte et al. (2012)	Ireland
	Leached N reduced by 30kgN/ha = 0.11tCO_2e/ha	Cameron et al. (2002) (cited in O’Hara, 2003)	New Zealand
Reduce amount of applied N	0.06tCO_2e/ha/yr	Pellerin et al. (2013)	France
Fieldwork CO_2 – increased diesel use	-0.062tCO_2e/ha/yr	Pellerin et al. (2013)	France

Costs elements and cost-effectiveness

One-off costs can arise if the cover crop system requires investment in specialized seeders or major adjustments in other equipment (such as planter or ploughs) to cope with the increased residue. In addition, farmers must sometimes invest in the appropriate equipment to “burn down” or terminate the growth of the cover crop prior to the planting of the commodity crop. Recurring costs arise from seed purchase and additional fieldwork for cultivation and destruction and incorporation of the cover crop. Savings may be made from reduced synthetic fertiliser application rates (Table 4).

Table 4. Main costs of cover crops*

Recurring costs/savings	Total cost or saving	Study	Location
Reduced fertiliser purchase Cover crop planting and destruction	(EUR 41/ha/yr) EUR 160/tCO_2e	Pellerin et al. (2013)	France
Purchase of seed and fuel costs associated with cultivation of the crop	EUR 71/ha/yr ~EUR 50/tCO_2e	Schulte et al. (2012)	Ireland
Seed (EUR 70/ha/yr) Cultivation/drilling (EUR 76/ha/yr) Incorporating crop residues (EUR 32/ha/yr)	EUR 178/ha/yr	Posthumus et al. (2013)	United Kingdom

* Figures in brackets are savings.
Source: Cited references.

Overall, cover crops are categorised as likely to have significant costs. The main driver of variation in cost-effectiveness is likely to be the cost of the cover crop cultivation and incorporation, which will depend on the efficiency of cultivation. This operation is unlikely to be cost-effective in areas where cultivation costs are high, or where there is a risk of yield reductions through the use of the cover crop.

Other costs and benefits

Cover crops are known to provide multiple other benefits. In particular, they can reduce emissions arising from fertiliser manufacture if synthetic fertiliser application is reduced (Pellerin et al., 2013: p. 45). Cover crops can also provide significant adaptation benefits, by decreasing soil erosion and increasing soil water retention capacity. They can improve water quality via reduced runoff (Schulte et al., 2012: 39; Kirk et al., 2012: 36; Wiltshire et al., 2014: 23).

On the other hand they may result in potential loss of production if they lead to switching from winter to spring cultivation (Wiltshire et al., 2014: 24). They are also associated with increased herbicide use (Schulte et al., 2012, Wiltshire et al., 2014: 23).

Implementation issues

Some policies have been encouraging the uptake of cover crops. The EU Rural Development Programme has been used to provide area-based payments for the sowing of cover crops in arable rotations during the fallow period. However challenges exist in terms of defining the baseline and estimating likely levels of additional uptake.

Cover crops need to be carefully targeted in order to achieve cost-effective mitigation. Hristov et al. (2013: p. 100) note that “Interactions with other soil conservation practices are significant (tillage system, for example) and must be considered when the goal of cover cropping is reducing whole-farm GHG emissions.” While Regina et al. (2013) show the high direct N_2O emissions that can arise from bare soil in boreal conditions, they note that “Data on the effect of practices like cover crops, catch crops, split application of fertilizer or precision farming are still lacking.”.

Potential barriers to the uptake of cover crops include: their establishment coincides with busy period in the farming calendar (Kirk et al., 2012: 34); they reduce the time to establish the following crop (Wiltshire et al., 2014: p. 21); they increase the cost of seeds and cultivation (Kirk et al., 2012: p. 34, Wiltshire et al., 2014: 21); and that they are incompatible with some other farm practices, such as post-harvest grazing (Wallander, 2013). Establishing or destroying the cover crop in wet conditions can presents the risk of damage to soil (Kirk et al., 2012: p. 34), and there is a risk of cover crops implying a negative effect on yield of following crop (Wiltshire et al., 2014: p. 21). Concerns about herbicide use and resistance, and the lack of suitable land have also been raised (Wiltshire et al., 2014: p. 21). For example, cover crops are better suited to light soil types, due to the spring ploughing requirement, and light-textured free-draining soils to enable preparation of a good seedbed for the succeeding crop. They may also be more suitable where there is a relatively high spring rainfall as the cover crop could deplete soil moisture reserves.

4.2. Precision nutrient application[13]

Precision farming encompasses many technologies providing more precise information about the land and crops and thus allowing the farmer to respond to in-field variations by allocating fertiliser, plant protection products, irrigation, seeds, etc. in a differentiated manner rather than as indiscriminate field-level operations. So far, the main focus of developments has been on crop production, but precision farming technologies can be applied to grasslands as well.

Precision farming can be beneficial on fields where yield varies according to a predictable pattern due to differences in soil quality, weed infestation, drainage, etc. It also provides opportunity to reduce physical overlap between machinery passes. There are five main groups of technologies used in precision farming (Rains and Thomas, 2009).

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[13] This case study is partly based on Eory (2012).

1. Geographical Information Systems (GIS) are software to manage spatial data.
2. Differential Global Positioning Systems (DGPS) provides topographic information of the positions used in GIS with the accuracy needed in-field.
3. Sensors make measurements on soil properties, pests, crop health, etc. They can be placed on the field, or on the tractors, or they might be remote, such as aerial or satellite photography.
4. Yield Monitoring (YM) is measuring the crop yield during harvest, providing a yield map.
5. Variable Rate Technology (VRT) includes computer controllers and associated hardware to vary the output of fertilizer, lime, seeds, pesticide, etc. applied on the different zones of a given field.

In general, the level of spatial precision is ±40cm to ±2cm, requiring higher investments for the more precise systems. The most basic equipment allows for reduced machinery passes by visual aids to the driver (GPS + GIS technologies), while VRT application requires higher investment in auto steering machinery.[14]

Expected impacts on GHG emissions

The most important GHG impact of the technology is a reduction in nitrogen fertiliser use and a consequent reduction in the N_2O emissions from soils. The effects are not well-explored yet, some estimates are presented in Table 5.

Table 5. Abatement rates for precision nutrient application

Mitigation effect	Abatement rate	Reference	Location
Soil N_2O from fertiliser	5%	(Bates et al., 2009)	EU 27
Soil N_2O from fertiliser	15%	(ICF, 2013 et al.)	United States
Soil N_2O from fertiliser	34%	(ICF, 2013 et al.)	United States
Soil N_2O from fertiliser	0.2 t CO_2e/ha	(Moran et al., 2008)	United Kingdom

Source: Cited references.

Costs elements and cost-effectiveness

Financial benefits from precision farming include reduced fertiliser and agrochemical use, reduced fuel use, higher yield and improved crop quality (ICF, 2013). Estimates for these benefits can be up to EUR 80 ha^{-1} (Bates et al., 2009; Boyer et al., 2011; Godwin et al., 2003; HGCA, 2009).

The one-off costs of equipment (hardware and software) purchase and training is in the range of EUR 6 000-50 000 (HGCA, 2009; ICF, 2013), with additional annual costs of operation and maintenance and soil/crop monitoring.

The range of cost-effectiveness estimates is wide (Table 6). The estimated cost-effectiveness largely depends on three elements: the cost of the equipment, the size of the farm, and the assumption about GHG savings. For example, cost-effectiveness of the one specific technology in the US (GreenSeeker^{TM} technology, which detects the crop status and adjusts nitrogen application rates accordingly) was estimated to range between EUR <0 and 332/t CO_2e, varying with the assumed N_2O emission reduction impact (low and high emissions reduction scenario assumed 15% and 34% reduction in N_2O emissions, respectively) (on average EUR 29/t CO_2e for the low and EUR 66/t CO_2e for the high emission scenario), size of farm (on average EUR 7/t CO_2e for 400 ha and EUR 108/t CO_2e for 100ha farms), with the type of the cereal (on average EUR 13/t CO_2e for maize and EUR 82/t CO_2e for wheat) and with the region (on average EUR 21/t CO_2e for the Corn Belt and EUR 62/t CO_2e for the Northern Plains) (ICF, 2013). Other important drivers might include fertiliser and crop prices and the interest rate.

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[14] Personal communication with R.M. Rees (SRUC).

Additionally, as with every mitigation measure, differences between studies can arise from the different definitions of the mitigation measures and from different assumptions on variables beyond those mentioned above.

Table 6. Cost-effectiveness estimates for precision nutrient application*

Cost-effectiveness	Reference	Location
<EUR 0/t CO_2e, low costs systems on cereal farms >80 ha	(Godwin et al., 2003)	United Kingdom
<EUR 0/t CO_2e, high cost systems on cereal farms >250 ha	(Godwin et al., 2003)	United Kingdom
EUR 143/t CO_2e	(Amann et al., 2008)	EU 27
EUR (175)/t CO_2e	(Bates et al., 2009)	EU 27
EUR 212/t CO_2e	(Hoglund-Isaksson et al., 2010)	EU 27
<EUR 0 to EUR 39/t CO_2e, 400 ha farms	(ICF, 2013)	United States
EUR 6 to EUR 332/t CO_2e, 100-200 ha farms	(ICF, 2013)	United States

* Figures in brackets are savings.
Source: Cited references.

Other effects

Precision farming can generate other benefits besides emission reduction. Via improved nitrogen efficiency, precision farming can first reduce nitrogen leaching and thus diminish diffuse water pollution. But it can also reduce land compaction due to fewer machinery runs, use less fuel and therefore generate fewer fuel-associated GHG emissions. Precision farming can also contribute to lower soil and water pollution when it induces decreases in agrochemical use (Bongiovanni and Lowenberg-Deboer, 2004).

Implementation issues

During the past decade, the number of farmers using simpler or more complex precision farming technologies has been growing steadily, for some crops and in some countries it is used on 5-10% of farms (e.g. wheat and corn farmers in the United States, farmers in general in Germany, grain growers in Australia), but due to the high capital investment required, precision farming has been implemented mainly on farms bigger than 200 ha (Diekmann and Batte, 2010; ICF, 2013; Pedersen et al., 2001; Reichardt et al., 2009; Robertson et al., 2012). In the future an increasing trend in crop and input prices and decreasing technology costs might make precision farming profitable on medium size farms as well.

The following barriers were mentioned mostly by farmers in the United Sates, Europe and Australia (Diekmann and Batte, 2010; Reichardt et al., 2009; Reichardt and Jurgens, 2009): low awareness, time requirements to get used to the technology, lack of technical knowledge, the incompatibility of machines of different manufacturers, the high cost of implementation (and the associated opportunity cost) and the difficulty in quantifying the benefits.

4.3 Nitrification inhibitors

Soil N_2O emissions are the second biggest category of agricultural emissions recorded within the OECD greenhouse gas inventories. They arise primarily from the application of (synthetic and organic) N to arable crops and grasslands, and from the direct deposition of N by grazing animals. Nitrification inhibitors (NIs) can reduce soil N_2O emissions by slowing the rate of conversion of fertiliser ammonium to nitrate. This means that the rate of conversion of nitrate to nitrous oxide (or dinitrogen) is decreased and emissions of nitrous oxide decrease. NIs can lower emissions by a) reducing direct N_2O emissions, b) reducing nitrate leaching and volatilisation and subsequent indirect N_2O emissions, c) increasing grass/crops yield and/or decreased amounts of fertiliser N applied – decreasing the amount of synthetic N applied will reduce the emissions arising from fertiliser manufacture (although this will be offset by the energy used to manufacture the NIs)— and d) decreasing the number of fertiliser applications (Weiske et al., 2007), leading to a reduction in the amount of energy used for field work.

Expected impacts GHG emissions

The use of nitrification inhibitors and slow release fertilisers has been studied extensively (Smith et al., 1997; Merino et al., 2002; Di and Cameron, 2003; Di and Cameron, 2004; Ball et al., 2004; Di et al., 2007). Pioneering work in New Zealand has shown that the application of dicyandiamide (DCD) to grazed grassland soils can reduce emissions of N_2O, mainly from urine patches, by up to 82% (Di and Cameron, 2002).[15] This work also demonstrated that DCD applications could also increase herbage production and more than halve the nitrate concentration in drainage water, providing an added economic incentive to reduce N losses. A methodology has been developed to incorporate the use of DCD and urease inhibitor into the agriculture sector of the New Zealand GHG inventory (see New Zealand Government 2014, p190-1). A more recent meta-analysis concluded that NIs could reduce N_2O by 31% to 44% (Akiyama et al., 2010). Estimates of the abatement rates are provided in Table 7.

Table 7. Abatement rates for nitrification inhibitors

Mitigation effect	Abatement rate	Source	Location
Reduction in soil N_2O	0.3 tCO_2e/ha/year	Moran et al. (2008: 45)	United Kingdom
	51% decrease in soil N_2O	Weiske et al. (2007: 32)	Germany
	DCD: soil N_2O down by 20-40%, fertiliser application reduced by 6.5-13% Agrotain*: soil N_2O down 5%, fertiliser reduced by 8%	ICF (2008: 48) ICF (2008: 48)	New Zealand
	DCD: 67% reduction in $EF_{3PRP,CPP}$ and 53% reduction in $Frac_{LEACH}$ Urease inhibitors: 45% reduction in $Frac_{GASF}$	New Zealand Government (2014, p190-1)	New Zealand
	30% decrease in soil N_2O	Bates et al. (2009: 28)	EU 27
	31% to 44% decrease in soil N_2O	Akiyama et al. (2010)	Various
Increase in production	Production increase of 7.5% to 15%	ICF (2008: 48)	New Zealand

Source: Cited references; *N-[n-butyl] thiophosphoric triamide.

Costs elements and cost-effectiveness

There are no significant one–off costs (though some time may be required to learn how to use the NIs efficiently). The main recurring cost is the purchase of NIs, which can vary depending on the crop and type of NI (Table 8). These costs are partly offset by the recurring benefits that accrue in terms of: (a) reduction in the number of fertiliser applications, and (b) reductions in the amount of fertiliser applied and/or yield increases. Estimates of the cost-effectiveness per t of CO_2e abated are given in Table 9.

The cost-effectiveness of nitrification inhibitors is sensitive to a number of factors. First, climatic conditions and soil type matter: "DCD is known to be somewhat less effective in warmer areas (Edmeades, 2004) and areas with acidic soils (de Klein et al., 2001)." ICF (2008: p. 57), see also (ICF, 2013: p2.38). Stocking rates may also have an effect "it is likely that the technology will be only feasible (i.e. economically viable) on soils where stocking rates are high and where emissions reductions are large." Schulte et al. (2012: p. 13).

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[15] Note that DCD has been voluntarily withdrawn from the market in New Zealand due to customer concern over low residue levels in milk products. There is no risk to humans from these levels of inhibitor in milk products.

Table 8. Estimates of the costs of nitrification inhibitors

Recurring costs	Total cost	Study	Location
Total	EUR 32 to EUR 61/ha/year	Moran et al. (2008 : p. 48)	United Kingdom
Purchase of NI	Agrotain EUR 19/ha/year	ICF (2008 : p52)	New Zealand
	DCD EUR 87/ha/year	ICF (2008 : p52)	
Purchase of NI	Nserve EUR 15/ha/year	ICF (2013 : p2.40)	
	Agrotain EUR 4 to EUR 10/ha/year	ICF (2013 : p2.40)	

Table 9. Estimated cost-effectiveness for nitrification inhibitors*

Range of cost-effectiveness	Units	Study	Location
107 to 202	EUR/tCO$_2$e	Moran et al. (2008: 49)	United Kingdom
(19.4) to 9.2	EUR/tCO$_2$e	Weiske et al. (2007)	Germany
(1903) to 602	EUR/tCO$_2$e	ICF (2008: p55)	New Zealand
>55	EUR/tCO$_2$e	Amman et al. (2008: p43)	EU 27
10	EUR/tCO$_2$e	Bates et al. (2009: p54)	EU 27
>450	EUR/tCO$_2$e	Schulte et al. (2012: p33)	Ireland
48 to 296	EUR/tCO$_2$e	ICF (2013: p2.41)	United States
61	EUR/tCO$_2$e	Pellerin et al. (2013: p30)	France

* Figures in brackets indicate savings.

Other costs and benefits

The environmental impact of NI manufacture should be offset by the reduced fertiliser manufacture. Other potential benefits include: reduced soil compaction due to fewer fertiliser applications (Weiske et al., 2007: 34), and reduced N leaching, leading to improved water quality (Schulte et al., 2012). Some potential negative impacts have also been cited, such as: possible inhibition of soil methane oxidation capacity (Weiske et al., 2007: 34), plant toxicity, and increased NH_3 volatilisation (Bates et al., 2009: 28).

Implementation issues and opportunities

The costs can be significant and the efficacy and cost-effectiveness are highly variable depending on factors such as the type of NI, crop, soil type and climatic conditions, which means that their support and use need to be carefully targeted in order to maximise the cost-effectiveness. The current rates of NI use are low in some OECD countries (such as the United Kingdom), which means that there should be scope for reductions in the purchase cost and improvement in cost-effectiveness as uptake increases. Finally, analysis of the mitigation arising from NIs should take into account potentially additional significant off-farm GHG emission reduction effects. These could arise in response to reduced fertiliser use (and manufacture) or from increased yields, which would lead to a reduction in production (and emissions) elsewhere.

4.4 Land use change from grassland to forest

Carbon is sequestered at different rates for different land uses, so encouraging (or in some cases preventing) certain land use changes has the potential to aid mitigation efforts. This case study focuses on the afforestation of grassland, which can mitigate GHG emissions in three main ways: sequestration with increase in above ground carbon storage; sequestration with an increase in below ground carbon storage; and the substitution of higher carbon fuels and materials (e.g. steel or concrete) with forest products.

Expected impacts on GHG emissions

Estimates of the abatement rates are provided in Table 10. It should be noted that sequestration abatement during forest expansion is a one-off opportunity; once a forest reaches its full size it will no longer sequester significant additional carbon from the atmosphere. In contrast sequestration in harvested biomass may be done year after year, offering ongoing opportunities to store carbon in long-life wood products such as timber housing frames.

Table 10. Abatement rates for afforestation of grassland

Mitigation effect	Abatement rate	Source	Location
Increase in above and below ground carbon storage	11.8 tCO_2e/ha/year	Radov et al. (2007: 37)	United Kingdom
	18.4 tCO_2e/ha/year	Moran et al. (2008)	United Kingdom
	3.7 to 13.2 tCO_2e/ha/year	ADAS (in Valantin, 2012: 16)	United Kingdom
	10.3 tCO_2e/ha/year	Sustainable Energy Ireland (2009, p160)	Ireland
Substitution of higher carbon fuels and materials	Fuels : 5.2 tCO_2e/ha/year	Moran et al. (2008)	United Kingdom
	Materials:		
	52.6 tCO_2e/ha/year	Moran et al. (2008)	United Kingdom
	6.9 tCO_2e/ha/year	ADAS (in Valantin, 2012: 16)	United Kingdom

Costs elements and cost-effectiveness

The main costs elements are given in Tables 11 and 12, and estimates of cost-effectiveness are shown in Table 13.

The results in Table 13 show some variation both within and between studies. Stavins and Richards (2005: iv) summarise the main factors affecting the cost-effectiveness of forest carbon sequestration as: the tree species involved; the opportunity cost of the land; the disposition of biomass through burning, harvesting, and forest product sinks; anticipated changes in forest and agricultural product prices; the analytical methods used to account for carbon flows over time; the discount rate employed in the analysis; and the policy instruments used to achieve a given carbon sequestration target.

The opportunity cost of land is particularly challenging to predict as the gross margin per hectare can vary a great deal spatially depending on the productivity of the land. It can also vary over time depending on factors such as the cost of inputs, price of commodities and policy context.

It should be noted that, assuming continued increase in global demand for food commodities, and the progressive decarbonisation of the energy sector, the cost-effectiveness of energy substitution options may decrease in the medium to long term.

Table 11. Main one-off and recurring costs and benefits of afforesting grassland

	Costs	Benefits
One off	Establishment Loss of land value Harvesting	Sale of harvested products
Recurring	Thinning Income foregone	Sale of thinnings

Table 12. Estimates of the costs and benefits of afforesting grassland*

One-off costs/savings	Total cost or (saving)	Study	Location
Establishment cost	EUR 1,588 to 3,810/ha	Radov et al. (2007)	United Kingdom
Establishment cost	EUR 1,588/ha	Moran et al. (2008)	United Kingdom
Establishment cost	EUR 1,664 to 6,858/ha	ADAS (Valantin, 2012)	United Kingdom
Establishment cost	EUR 3500/ha	Sustainable Energy Ireland (2009, p160)	Ireland
Loss of land value	EUR 3,175 to 9,525/ha	Radov et al. (2007)	United Kingdom
Sale of harvested timber	(EUR 9,525 to 10,541/ha)	Moran et al. (2008: 95)	United Kingdom
Recurring costs/savings	**Total cost or (saving)**	**Study**	**Location**
Maintenance (thinning etc.)	(EUR 1905/ha for 4 thinnings)	Moran et al. (2008: 95)	United Kingdom
Income foregone	Highly variable EUR 64 to 445/ha	Valantin (2012: 6)	United Kingdom
Land rental	EUR 300/ha/year	Sustainable Energy Ireland (2009, p160)	Ireland
Timber sales	(EUR 87/ha/year)	Sustainable Energy Ireland (2009, p160)	Ireland

* Figures in brackets are savings.

Table 13. Estimated cost-effectiveness for afforestation of grassland

Costs/savings	Total cost or (saving)	Study	Location
Sequestration and substitution	(9 to 3 EUR/tCO$_2$e)	Moran et al. (2008)	United Kingdom
Sequestration and substitution	(77) to 131 EUR/tCO$_2$e	ADAS (in Valantin, 2012)	United Kingdom
Sequestration and substitution		Price (in Valantin, 2012)	United Kingdom
Sequestration	39 to 50 EUR/tCO$_2$e	EPA Queensland (2008: 78)	Australia
Sequestration	NPV = 3/EUR/tCO$_2$e 6 to 18 EUR/tCO$_2$e (1997)	Stavins and Richards (2005: v)	United States
Sequestration	30 EUR/tCO$_2$e	Sustainable Energy Ireland (2009, p79)	Ireland

Other costs and benefits

Other costs and benefits are likely to be specific to the plantation type and management. However, any assessment of the impact of this measure should take into account the impact of the displaced production.

Implementation issues

Several issues may arise when considering this option. First, the identification of suitable implementation sites is not trivial. Second, selecting appropriate discount rates for quantifying the cost-effectiveness and quantifying displacement effects are difficult; agroforestry may be preferred in some cases to avoid loss of production and displacement of emissions. There are also risks that sequestered carbon could be released via processes such as forest fires or the decay of harvested wood products. Valatin (2012: 7) has argued that such “non-permanence risks do not appear to have been adequately accounted for in previous studies”.

4.5 Fat supplementation in ruminant diets[16]

Fat supplementation is one of various feeding practices aiming to reduce GHG emission from livestock operations (others include, for example, reduced protein content of the diet and feed supplements). This measure is based on increasing some of the commonly used feed ingredients in the diet. A traditional ruminant diet, depending on whether the animal is mostly grazing or fed a high proportion of concentrates (non-forage feeds high in energy and/or protein content, e.g. a mixture of grains, soybean meal, beet pulp, etc.) contains 1.5-3 dry matter % (DM%) fat. Increasing the fat content reduces enteric CH_4 emissions from the rumen via biological processes in the digestive system. The CH_4 reduction is proportional to the fat content, but, due to potential health issues and practical aspects, a limit of 5-6 DM% total fat content is necessary. Various supplementary fat sources exist: whole seeds (e.g. rapeseed, linseed, soybean), plant oils (e.g. sunflower oil, rapeseed oil, palm oil, coconut oil), and special products (e.g. Energy Booster, Megalac). Alternative sources can be the high-oil by-products of the biofuel industries. Some farmers with high-productivity herds are already supplementing fat to their animals, to boost the energy content of the diet. However, even for those animals the total fat content might be below 5-6 DM%. The additional uptake potential is even higher in those herds which are currently not receiving fat supplementation, though the incorporation of fat in the diet for animals mainly fed on forages (i.e. grazing and cut grass) might not be practical.

Expected impacts on GHG emissions

The main impact of fat supplementation is a reduction in enteric CH_4 emissions proportional to the fat content (Table 14). Two mechanisms might partially off-set this mitigation: (a) a potential increase in CH_4 emissions from manure storage (if the increased fat content reduces the digestibility of the whole diet, the undigested organic matter in the manure increases, leading to higher methane emissions from slurry storage, though there is limited scientific evidence about this effect) and (b) a potential increase in emissions related to the production of the high fat-content feedstuffs (emissions related to the production of the high starch- or protein-content feedstuff may concurrently decrease). The latter depends on the feed ingredients and their cultivation practices; to minimise the negative effect farmers should be encouraged to use low emission intensity fat sources (i.e. crops with relatively low GHG emissions per kg product). Generally crops grown in Europe (linseed, oilseed rape) are associated with significantly lower GHG emissions from land use change than those grown in tropical regions (e.g. coconut, palm oil or soybean).

Table 14. Abatement rates for increasing the fat content of ruminant feed to 5% DM

Mitigation effect	Abatement rate	Reference	Location
Enteric CH_4 emissions	With every 1% fat added CH_4 emissions are reduced by approximately 4% across all ruminants	Beauchemin et al. (2008), Grainger and Beauchemin (2011), Eugene et al. (2008), Moate et al. (2011), Martin et al. (2010), Doreau et al. (2014); Pellerin et al. (2013)	Developed countries
Land use change	Cattle: +100 to +191 $kgCO_2e$/animal/year	Pellerin et al. (2013: 59) - based on standard LCA data provided by the Dia'terre® – Ges'tim database and INRA.	Global, related to feed use for cattle production in France

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[16] This case study is partly based on Frelih-Larsen et al. (2014).

Costs elements and cost-effectiveness

In most cases farmers are likely to incur increased feeding costs from purchasing the supplementary oily seeds, by-products or oils, as they are in most cases more expensive than the concentrate ingredients they are replacing – however, high variations between feed ingredients within a region and the same ingredients among regions are likely and fluctuations with time are inevitable. Cost-effectiveness estimates range from a net saving of 70 to a cost of ~EUR 500/t CO_2e (Table 15), the variability likely to be mainly driven by assumptions about feed costs (e.g. Bates, 2001, estimate of net savings had an underlying assumption of no increase in the price of the ration).

Table 15. Cost-effectiveness estimates of fat supplementation in ruminant diets*

Cost-effectiveness	Reference	Location
EUR (70)/t CO_2e	(Bates, 2001)	EU 15
EUR (69)/t CO_2e	(Graus et al., 2004)	Global
EUR 499 to EUR 508/t CO_2e	(ICF, 2008)	New Zealand
EUR 137 to EUR 262/t CO_2e	(Bates et al., 2009)	EU 27
EUR 79 to EUR 158/t CO_2e	(Henderson in prep.)	Global
EUR 223 to EUR 335/t CO_2e	(Pellerin et al., 2013)	France

* Figures in brackets are savings.

Other effects

On the positive side, the additional fat can increase the growth rate and the milk yield. Moreover, the milk fat content and composition might improve (Grainger and Beauchemin, 2011; Marette and Millet, 2014; Patra, 2012). This is not taken into account in Table 15 and could improve cost-effectiveness.

However, if the fat content exceeds 5-6 DM% the rumen might be disturbed decreasing milk yield and growth rate (Grainger and Beauchemin, 2011; Pellerin et al., 2013). Furthermore high-fat ingredients originating from tropical areas can be associated with a biodiversity loss linked to land use change.

Implementation issues

It is challenging to regulate a dietary change which is based on a shift of existing feed ingredients if there are unclear economic benefits. Programs to support only the additional, increased fat content which goes beyond the baseline the farmer might have used for an increased performance is difficult, while regulatory approaches might find the monitoring problematic. Information provision may already improve farmers' awareness and encourage target nutrition planning.

Potential barriers to uptake include the practical issues around feeding mentioned above (for diets with less than 20 DM% concentrates or not based on a total mixed ration, the high fat content can lead to difficulties in storage and mixing) (Pellerin et al., 2013), and the costs of the required ingredients (Hristov et al., 2013; Pellerin et al., 2013). Another key uncertainty is that the long-term persistence of the mitigation effect has not been consistently proved yet (Hristov et al., 2013; Martin et al., 2010).

4.6 Breeding to reduce enteric CH_4

Genetic improvement of livestock is a continuous process bringing cumulative changes in animal performance. The improved genetic merit becomes available to the farmers via purchased breeding stock or semen. In many countries the industry uses breeding indices to help the farmers in this process. A breeding index is an overall score for genetic merit combining several traits, with varying emphasis on productivity (e.g. yield) and fitness (e.g. longevity, fertility, etc.) (Miglior et al., 2005). Commercial breeding has been targeting economic efficiency, which is closely linked to productivity and the fitness of the animal. Higher productivity means using less input for the same amount of output, consequently generating less waste, including greenhouse gases. Indeed, as shown by a study carried out in the United Kingdom, this breeding goal indirectly reduced greenhouse gas and ammonia emissions across livestock species in the past (Table 16), and is predicted to bring further environmental benefits (Genesis Faraday, 2008).

Genetic improvement can bring a reduction in greenhouse gases in three different ways (Wall et al., 2010):

- Indirect effect via improved productivity and efficiency of the animal (e.g. more milk with the same number of cows);
- Indirect effect via improved efficiency of the herd/flock (e.g. smaller number of followers required due to reduced culling of cows);
- Directly reduced enteric CH_4 emissions (for ruminants, like cattle and sheep, see, for example http://www.nzagrc.org.nz/media.html).

The first two effects, as discussed above, are already included in commercial breeding goals. Still, there is scope for further and faster progress on the environmental effects, in particular via greater rates of genetic improvement (e.g. by development of new technology, better measurement and recording techniques, optimisation of breeding schemes, etc., see Genesis Faraday, 2008). A higher emphasis in the breeding indices to traits related to fertility and fitness can also result in progress. And a wider and faster penetration of the improved genetic merit into commercial herds/flocks can have significant effects. For example, while the national dairy herd in the United Kingdom shows significant genetic improvements, the use of indices and the speed of genetic improvement in the beef herd are much slower (Moran et al., 2008).

The economic benefits of the third possibility (selecting for low CH_4 emissions) are not so evident. Nevertheless, in recent years there has been a movement in the breeding goals to include societal aspects, e.g. welfare, biodiversity (Wall et al., 2010). The inclusion of reduced CH_4 emissions in the breeding goals is desirable but might require policy support.

Expected impacts on GHG emissions

The impacts on GHG emissions will be wide-ranging, depending on the species and the share of the different traits in the genetic improvement achieved. For non-ruminants (pigs, poultry) an overall reduction in emissions (N_2O and CH_4) is expected from the improved productivity and efficiency. For ruminants a reduction in enteric CH_4 emissions will also be achieved, and this mitigation will be bigger with an increased emphasis of the inclusion of low CH_4 traits in the breeding goals.

Table 16. Abatement rates for breeding to reduce enteric CH_4

Mitigation effect	Abatement rate	Reference	Location
All GHG emissions (LCA approach, per product basis)	During 20 years (between 1988-2008) emission intensity dropped by 15-25% for chicken, pigs and dairy[a]	(Genesis Faraday, 2008)	United Kingdom
	During 20 years (1988-2008) emission intensity dropped by 1% for beef and sheep[a]	(Genesis Faraday, 2008)	United Kingdom
Enteric CH_4 (ruminants)	14% abatement (per animal) to be achieved over ten years	(ICF, 2008)	New Zealand
	5% abatement (per herd) to be achieved over ten years	(Bates et al., 2009)	EU 27
	No CH_4 effects, but 22.5% milk yield increase to be achieved over 15 years	(Moran et al., 2008)	United Kingdom

Source: a. These historic changes include emission savings beyond genetic improvement (i.e. mitigation from changes in farm management, like feeding, herd management).

Costs elements and cost-effectiveness

The on-farm cost of this measure is usually assumed to be zero. It is likely that even if there is a need for switching from natural service to artificial insemination for genetic improvement, there is likely to be no significant cost increase (Jacobsen, 2010). On the other hand economic benefits will occur as a result of improved efficiency (higher yield and/or less resource used). Therefore most of the cost-effectiveness estimates are negative (Table 17).

Table 17. Cost-effectiveness estimates for breeding to reduce enteric CH_4*

Cost-effectiveness	Reference	Location
EUR (4,576) to EUR 0/t CO_2e (fertility and productivity)	(Moran et al., 2008)	United Kingdom
EUR 11 to EUR 18/t CO_2e (low CH_4 emissions) (assumed a cost of EUR 12/animal)	(ICF, 2008)	New Zealand
EUR 0/t CO_2e	(Bates et al., 2009)	EU 27
EUR (4,576) to EUR (128)/t CO_2e (fertility and productivity)	(MacLeod et al., 2010b)	United Kingdom
EUR (48)/t CO_2e	(Graus et al., 2004)	Global

* Figures in brackets are savings.

Other effects

Some other effects can affect the cost-benefit balance. On the one hand, the improved productivity brings additional environmental co-benefits, e.g. reduced ammonia emissions and reduced diffuse water pollution. Second, the increased yield might necessitate the use of more concentrates for cattle, with the possible negative effect on land use change from grasslands to arable land (Moran et al., 2008). Third, if achieving the potential efficiency gains from breeding necessitates an increased animal confinement, negative animal welfare impacts might arise. Finally, there is a risk of maladaptation with this measure. The increased emphasis on efficiency and reduced GHG emissions might reduce genetic diversity and might be contrary to the effort of developing hardier breeds which are more suitable to changing weather conditions and increased disease risks.

Implementation issues

A wider and faster penetration of the improved genetic merit into commercial herds/flocks can be supported by raising awareness amongst farmers about the breeding indices, and, where not widely practiced, raising awareness also on artificial insemination. Low profitability may act as a barrier to uptake in some countries.

The time required for a wide penetration of higher genetic merit animals in the national herds is an important consideration, especially for the low CH_4 traits. Once market or policy incentives exist, time is required for the low CH_4 breeding stocks and semen to be available and then also for the uptake by farmers. Thus the abatement effect and the uptake are both likely to increase slowly over decades.

Potential barriers to uptake include a low awareness and/or a low willingness to adopt genetic improvements in some countries (resulting from particular social or demographic profiles within their beef sectors) and the fact that farmers might consider the low CH_4 traits as not economically valuable.

4.7 Anaerobic digestion

Anaerobic digestion (AD) is a technology to convert organic material into biogas (a combination of CH_4, carbon dioxide and some other gases) which is subsequently combusted to produce electricity or heat. In agriculture animal waste is a good feedstock for the process, as are food waste, energy crops and crop residues. Apart from providing renewable energy, the benefit of the anaerobic digestion of manure is that the CH_4 emissions escaping during storage are hugely reduced as most of the CH_4 is captured and during the combustion transformed into carbon dioxide.[17] The digestate can be used as a fertiliser.

A few different technological solutions exist, and the choice of technology is partly defined by the type of manure on the farm, by existing facilities, by the climatic zone the farm is situated in (the CH_4 efficiency of the unheated lagoon digesters can be very low in low temperatures) and by investment capabilities. Additional organic materials are often co-digested with the manure, mostly crops, like maize (Kalamaras and Kotsopoulos, 2014), as these feedstocks usually provide a better CH_4 yield.

An anaerobic digester can be built to serve one single farm, or, if animal production density allows centralised anaerobic digester, can treat animal waste from neighbouring farms.

Expected impacts on GHG emissions

AD reduces CH_4 emissions from liquid manure storage via capturing the biogas. The amount of GHG reduction varies according to what were the emissions from the original storage, which, in turn, depends e.g. on the type of storage, on the temperature, whether the storage was covered or not. Added to this savings in emissions comes the indirect effect of replacing energy generated from fossil fuels; this replacement effect depends on the fuel mix used for electricity generation in that particular country (Table 18).

Table 18. Abatement rates for anaerobic digestion

Mitigation effect	Abatement rate	Reference	Location
CH_4 from liquid manure stores	85%	(EPA, 2013)	United States
	90%	(Bates et al., 2009)	EU 27
	75-93%, decreasing with lower annual temperature	Own calculations based on IPCC (IPCC, 2006) emission factors, 20% pre-digestion storage loss, 3% leakage, 24% net electricity generation efficiency and 0.33 kg CO_2e /kWh marginal emission factor for electricity	General, temperate climate

Costs elements and cost-effectiveness

AD is a capital intensive technology, the high upfront costs make it profitable only on bigger farms or if manure is brought in from neighbouring farms (centralised AD). Beyond the capital costs the annual operating costs and maintenance costs can be significant due to the complexity of the system. However, income is generated through the sales of the energy or the sales of the biogas. The energy expenditures on the farm can also be reduced by utilising the heat generated. The cost of a heat distribution infrastructure can be a key factor influencing profitability.

Capital costs are reported to be in the range of EUR 2 700/kW to EUR 11 000/kW, while the operating costs are estimated to be around 2-6% of the capital investment (Hardtlein and Eltrop, 2013; Lazarus and Rudstrom, 2007; MacLeod et al., 2010; Pellerin et al., 2013; The Andersons Centre, 2010; Walla and Schneeberger, 2008; Yiridoe et al., 2009).

The cost-effectiveness is highly dependent on a range of factors, including: "the size of the operation, manure storage method, the price of electricity, on farm energy (heating) expenditures, the ability to sell electricity not used on the farm, and—if there is a carbon off set market—the price of carbon" (Kay and Sneeringer, 2011, p3). The additional feedstock used in the digester is also an important factor, the climatic zone where the digester is situated as well. These factors and variability in cost data partly explain the wide range of cost-effectiveness estimates in Table 19.

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[17] CH_4 has a 100-year global warming potential equal to 25 times that of CO_2 (IPCC, 2007).

Additional benefits of AD include its propensity to control odour, the destruction of pathogens and weed in the manure, and improved slurry handling.

However, a drawback of AD might be an induced increase in feedstock crops production potentially at the expense of grasslands or natural areas, and the impacts arising from the transportation of large volumes of raw manure and digestate for centralised AD plants.

Table 19. Cost-effectiveness estimates for anaerobic digestion *

Cost-effectiveness	Reference	Location
Centralised digesters		
14 EUR/t CO_2e	(Moran et al., 2008)	United Kingdom
0 to 153 EUR/t CO_2e	(Amann et al., 2008)	EU 27
(48) to130 EUR/t CO_2e	(Bates et al., 2009)	EU 27
0 EUR/t CO_2e	(MacLeod et al., 2010b)	United Kingdom
On-farm digesters (across farm sizes)		
(3) to (2) EUR/t CO_2e	(Weiske and Michel, 2007)	Germany
(2) to 24 EUR/t CO_2e	(Moran et al., 2008)	United Kingdom
(20) to 62 EUR/t CO_2e	(ICF, 2008)	New Zealand
158 EUR/t CO_2e	(Smith et al., 2008)	Global
77 to 214 EUR/t CO_2e	(Bates et al., 2009)	EU 27
22 to 42 EUR/t CO_2e	(MacLeod et al., 2010b)	United Kingdom
8 to 693 EUR/t CO_2e	(Hoglund-Isaksson et al., 2010)	EU 27
150 EUR/t CO_2e	(Schulte et al., 2012)	Ireland
17 EUR/t CO_2e	(Pellerin et al., 2013)	France
0 to 635 EUR/t CO_2e	(ICF, 2013)	United States

* Figures in brackets are savings.

Implementation issues

Promoting the wider implementation of AD has been done through a range of policy instruments: targeted support for the capital investment, price support for the electricity sold. AD could also potentially benefit from carbon credits as the monitoring of the greenhouse gas savings is possible at a relatively low cost. The high number of AD plants in Germany compared to other countries in Europe and beyond is due to the favourable regulatory environment (Wilkinson, 2011).

At the same time, there are several barriers to the uptake of AD. In particular, high capital investment and the lack of infrastructure to feed the produced electricity into the national grid lead to significant external costs. Regulatory and market risks in terms of subsidies, contracts on how the farmer can sell the electricity and electricity prices can also play a role. The know-how required for the maintenance may discourage farm operations. Compatibility with other regulations (such as the Nitrates Directive in the EU) and potential restrictions on the use of some of the feedstocks (e.g. food waste) may also have an effect.

4.8 Improving energy efficiency in mobile machinery[18]

Energy is used for a wide variety of purposes in farming, such as: powering mobile machinery, environmental control (heating, cooling, lighting, ventilation, humidity control etc.), processing (e.g. cooling milk or drying grains), irrigation and drainage. The emissions arising from this energy use represent a small but significant proportion of the OECD total agricultural emissions. Recent studies

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[18] This case study is partly based on Frelih-Larsen et al. (2014)

(AgriClimateChange, 2013; AEA/FEC Services Ltd, 2010) have highlighted the importance of emissions from mobile machinery in particular.

Expected impacts on GHG emissions

AgriClimateChange (2013) reported the proportion of total on-farm GHG emissions arising from mobile machinery as ranging from 37% in vineyards to 5% on beef and rice farms. Potential fuel savings reported in the Efficient 20 database are given in Table 20.

Table 20. Average fuel savings potential for mobile machinery actions reported in the Efficient 20 database (Location: EU)

Action	Summary	Average % reduction in fuel use
Save tractor's use	Substituting tractors with more energy efficient machinery where possible.	13.0
Eco-driving	Smoother driving technique, maintaining the most efficient engine speed etc.	5.4
Economic power take-off	Using a take-off that saves fuel by enabling the tractor engine to be run at lower RPM.	15.4
Longer work sequence	Longer fields lead to less fuel used turning on headlands.	11.0
Adapt weights	Adjusting ballast to reduce tyre slippage and soil compaction.	5.7
Adapt implement's settings	For example, setting the plough to the optimal depth.	16.8
Tyre management	Choosing appropriate tyre type and pressure etc.	10.7

Source: Efficient 20 (2013):6.

Pellerin et al. (2013: 78) estimated a reduction in fuel consumption of 10% for engine testing (i.e. "passing tractors over an engine test bench (ETB), making it possible to optimise engine adjustment" Pellerin et al., 2013: 75) and 20% for eco driving. The actual reduction in fuel use achieved will vary from farm to farm depending on a range of factors such as: crop type, soil type, mode of cultivation and baseline tractor efficiency (Efficient 20, 2013: 3).

Cost elements and cost-effectiveness

One-off costs arising from the operation are: (a) time to learn how to improve energy efficiency, (b) purchasing equipment, and (c) modifying existing equipment. Recurring costs may arise from time required on an ongoing basis to, e.g. undertake field operations, monitor fuel consumption or attend further training, and machine maintenance (see Table 21).

Table 21. Recurring costs and savings of improved energy efficiency in mobile machinery (+ cost, saving)

Recurring costs/savings	Study	Location
-Reduction in fuel costs of between 5.4% and 16.8%	Efficient 20 (2013: 6)	EU
+Risk that some actions (e.g. eco-driving techniques) could lead to operations requiring additional time if not managed efficiently.	Efficient 20 (2013: 8)	EU

The evidence suggests that the net cost of improving mobile machinery energy efficiency is likely to be negative (i.e. the fuel savings should more than offset the expenditures) (AEA/FEC Services Ltd, 2010, Domingo et al., 2014: 15, Pellerin et al., 2013: 78).

Other costs and benefits

These will depend on the specific ways in which the efficiency is improved. For example, if reduced tyre pressures are adopted this could lead to reduced soil compaction with associated production and environmental benefits. In general there should be reduced upstream emissions arising from the production and transportation of fuel.

Implementation issues

There are several potential barriers to uptake of energy efficiency (AEA/FEC Services Ltd, 2010: 4; Efficient 20, 2013: 8). However, compared to other GHG mitigation measures, Domingo et al. (2014: 16) concluded that improving fuel use efficiency should be easy for farmers to implement and "could possibly be the best accepted measure by the farmers' community".

Rebound effects are a general problem with energy efficiency (see Sorrell, 2007). They are unlikely to be any significant issue with the use of mobile machinery, where the marginal benefit of additional usage is likely to decrease rapidly beyond a certain level of usage. However, AEA/FEC Services Ltd (2010: 12) caution that "improvements in the energy efficiency of vehicle engines does not axiomatically translate into reduced fuel consumption".

In general, the CE of energy efficiency may decrease over time as the emissions intensity of energy use (i.e. the emissions per unit of output) decreases in response to the development of more energy efficient equipment and the decarbonisation of electricity generation (AEA/FEC Services Ltd 2010: 8).

Uptake of energy efficiency measures will be driven by a combination of market forces (primarily increasing energy prices) and policy. Fuel subsidies reduce the incentive to improve energy efficiency and should therefore be avoided. Once there are clear private incentives to reduce energy, policy can help provide education and information. In their survey, Efficient 20 (2013: 8) found that "nearly the half of the farmers and foresters surveyed would like to save fuel without knowing how to do it." (p. 8), (i.e. they would like to save fuel but don't know how to do it).

4.9 Use of biological N fixation in crop rotations and in grass mixes[19]

Crops belonging to the family *Leguminosae* form symbiotic relationships with bacteria in the soil that allows them to fix atmospheric N and use this in place of N provided by synthetic fertilisers or manure. Leguminous crops, which can be grains or forages, are able to fix in excess of 300 kg N/ha/y making the N input comparable with quantities of synthetic or manure N applied to many crops. Legumes can mitigate GHG emissions in four main ways: (a) reducing direct emissions from N fertilisers; (b) reducing the CO_2e emissions from fertiliser manufacture; (c) reducing N leaching and subsequent indirect N_2O emissions; (d) reducing in the amount of N that needs to be applied to the following crop.

Expected impacts on GHG emissions

The main on-farm mitigation effect of legumes is via reduced or avoided nitrous oxide emissions (Table 22). The inclusion of legumes in rotations has also been shown to allow carryover of residual N to subsequent crops, thereby reducing the fertiliser requirement of subsequent crops and associated N_2O emissions (Buses et al., 2013).

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[19] This case study is partly based on Frelih-Larsen et al. (2014)

Table 22. Abatement rates for legumes in arable systems and on grassland

Mitigation effect	Abatement rate (AR)	Source	Location
Reduction in direct and indirect N_2O	Grain legumes 1.02 tCO_2e/ha/yr Forage legumes 0.17 tCO_2e/ha/yr	Pellerin et al. (2013)	France
Reduced fertiliser production	Grain legumes 0.95 tCO_2e/ha/yr Forage legumes 0.16 tCO_2e/ha/yr	Pellerin et al. (2013)	France
Total reduction in GHG*	Grain legumes 1.99 tCO_2e/ha/yr Forage legumes 0.33 tCO_2e/ha/yr	Pellerin et al. (2013)	France
Reduction in direct and indirect N_2O	Clover 0.5tCO2e/ha/yr	Moran et al. (2008, p43)	United Kingdom
Reduction in on-farm GHG	Substituting legumes for cereals: 1.19 tCO2e/ha/yr (barley) to 2.20 tCO2e/ha/yr (maize)	Dequiedt and Moran (2015)	France

*Including minor changes not specified in table.

Cost elements and cost-effectiveness

No significant one-off costs are predicted, but recurring costs would arise from reduced farm gross margins when replacing a cereal crop with a legume. Savings may be made from reduced synthetic fertiliser purchase costs (Table 23), and reduced field operations.

Table 23. Costs or savings of N fixation introduction in crop rotations

Total cost	Source	Location
Grain legumes 19 EUR/ha/yr Forage legumes (31) EUR/ha/yr Grain legumes 18 to19 EUR/tCO2e Forage legumes (189) to (169) EUR/tCO2e	Pellerin et al. (2013)	France
For clover: Yield reduced by 30%; N purchase cost reduced by 60%; Labour and machine costs reduced by 5%. Overall CE: 20 to 55 EUR/tCO2e	Moran et al. (2008, p47)	United Kingdom
Arable crops “this would be an inexpensive measure” Grasslands “could be neutral or even entail a negative cost”	Domingo et al. (2014, p27)	EU
Range of values depending on region and assumptions, average: 43 EUR/tCO_2e	Dequiedt and Moran (2015)	France

* Figures in brackets are savings.

Variation in cost-effectiveness is likely to depend on how much yield and income is foregone. These will be influenced by economic (i.e. crop and input prices) and biophysical parameters (i.e. variety, climate, soils and agronomy). This operation is unlikely to be cost-effective in areas where there is an unfavourable climate.

The emissions reductions (and therefore cost-effectiveness) from avoided fertiliser manufacture depend on the type of fertiliser displaced and its place of production. Ranges of GHG emissions (cradle to gate) for the most commonly used N-fertilizers are provided in Vellinga et al. (2013, p67).

Other effects

Potential ancillary benefits include: (a) improved water quality via reduced leaching of nitrate (Nemecek et al., 2008, Moran et al., 2008, p142); (b) reduced OECD demand for imported protein crops and consequent reduction in land use change in some protein crop exporting regions; (c) climate change adaptation benefits (when used as a cover crop) arising from decreased soil erosion and increased soil water retention capacity; (d) suppressed incidence of weeds and diseases (when used as a break crop in arable rotations); and (e) potential biodiversity benefits (Rees et al., 2014; Bues et al., 2013). Ancillary costs include greater yield variability in response to weather variability, and potential displacement of production if yields are reduced.

Implementation issues

Legume cultivation is widely applicable on different soil types in arable and grassland rotations; however, they are best suited to light soils types with moderate to high pH and P status. The residues left by legume crops can result in rapid losses of N, so it is important to ensure that ground is not left fallow following the incorporation of legume residues.

5. From mitigation measures to possible mitigation policy options: A preliminary discussion

Drawing clear policy messages from the literature on mitigation practices is challenging, due to the differences in scope, method and assumptions that make inter-study comparability problematic. Some examples of inter-study differences that can have a significant impact on the estimation of cost-effectiveness are given in Table 24. Studies comparing multiple measures with the same method in a specific country context are better placed to provide meaningful conclusions, as shown in Box 6 in the case of France.

In order to illustrate how CE can vary, the results for a separate subset of commonly studied mitigation measures in the reviewed international literature are compared in Figure 7.[20] These studies were thought to be broadly comparable as they use similar bottom-up cost engineering approaches, contain original cost data (rather than just reviews) and are sufficiently disaggregated in order to enable comparison. Results are presented for the measures that were most commonly included in the studies, i.e. those that appeared in five or more studies in the literature review. It should be noted that when the cost-effectiveness data was examined more closely, suitably transparent results were not always presented; therefore, in the diagram, some of the measures have cost-effectiveness estimates from less than five studies.

Figure 7 shows that the cost-effectiveness of a measure can largely vary between studies, even when broadly similar approaches are used. There can also be a wide range of cost-effectiveness within studies for some measures, such as optimising N fertilisation, though these ranges will, to an extent, simply reflect the scope of the studies (i.e. where the system boundaries are drawn and which costs and emissions categories are included within those system boundaries).

Table 24. Potential source of study incommensurability

Scope	Where is the system boundary drawn? Which emission categories are within the system boundary? Which costs and benefits are included (expenditures only, expenditures plus foregone income, opportunity cost etc.?)
Method and assumptions	Which method is used to determine the reduction in emissions, e.g. which emission factors and global warming potentials? How are the emissions arising from land use change calculated and allocated? What assumptions are made about soil carbon sequestration? Which discount rates are used? How was the uptake under business-as-usual and alternative policies estimated?

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[20] These are not corresponding exactly to the cases presented in section 4. Section 4 covers a wider range of practices, not all with comparable methods and data.

Box 6. Abatement potential and cost of ten technical measures: The case of France

On the behalf of the French Environment and Energy Management Agency (ADEME), the Ministry of Agriculture, Food and Forestry (MAAF), and the Ministry of Ecology, Sustainable Development and Energy (MEDDE), the French National Institute for Agricultural Research (INRA) conducted a study on the cost and abatement potential of ten technical measures to reduce greenhouse gas emissions from agriculture in France (Pellerin et al., 2013).

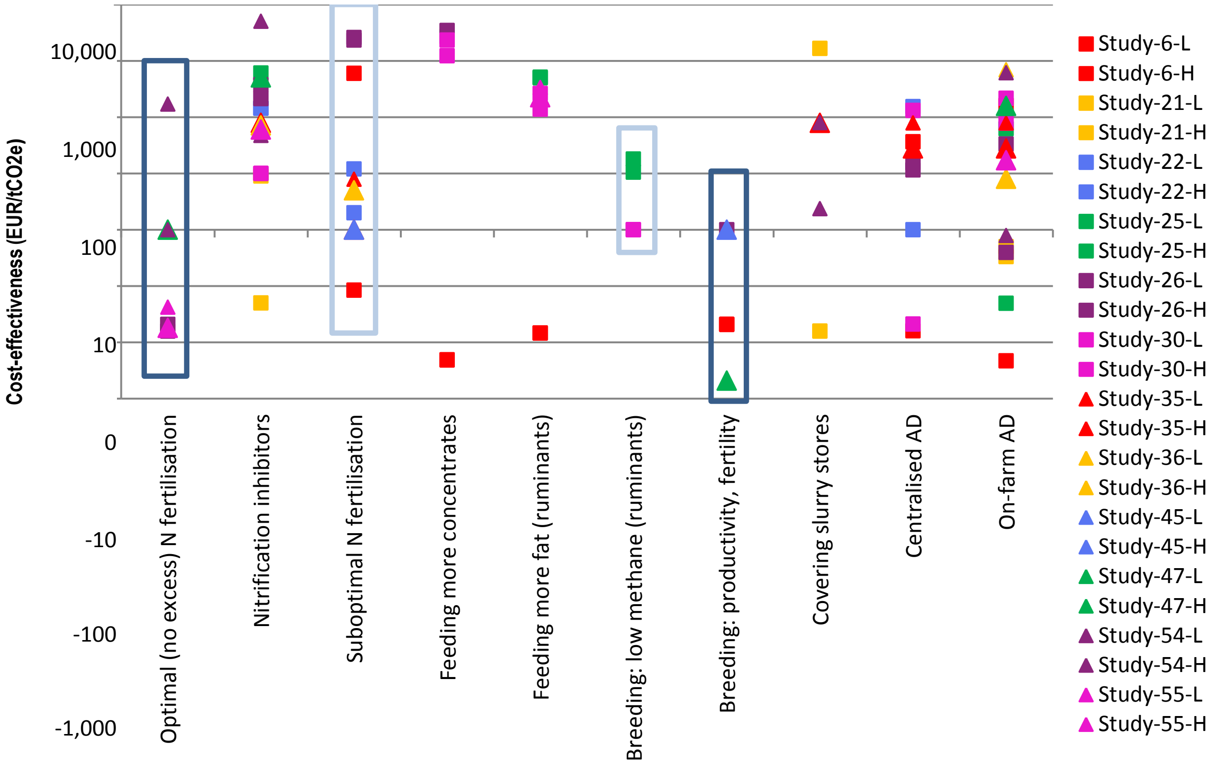
The selected measures fall under four main technical levers: (i) reduce the application of mineral nitrogen fertiliser, (ii) store carbon in soil and biomass, (iii) modify livestock diet, and (iv) recycle manure to produce energy and reduce fossil fuel consumption. Several criteria were used when selecting the measures for the study, including that the adoption of the measure should not reduce production more than 10%, the measure should focus on farm practices and not upstream or downstream in the sector, and the current availability of technology (measure). Annual GHG abatement potential of each measure is based on unitary estimates of abatement potential and cost, the applicability (regarding land area and number of animals) and the projection of the adoption of measures over the period 2010-2030.

Study results show that there are several measures whose costs are negative. These include grassland management (such as increasing a proportion of legumes in temporary grasslands and increasing lifespan of temporary grazing) and reduction of fossil fuel consumption (through improving the insulation and heating systems of livestock buildings and optimising diesel use of tractors via engine adjustment and adoption of eco-driving). Fertilizer management through adjusting application levels and timing as well as improved use and application of manure represent also measures with slightly negative costs and large abatement potential.

Moderate cost (less than EUR 25/CO_2-eq) abatement measures include reduced tillage and no-till as well as methanisation of livestock manure. High cost measures (greater than EUR 25/CO_2-eq) include land use and land cover related measures, such as hedges, grass buffer strips and cover crops. Overall the study results show that most of the abatement potential with negative costs is related to nitrogen management and that their value is increased when induced emissions (reduction of synthetic nitrogen fertilizer manufacture) and environmental co-benefits (water quality and air quality) are also considered.

Source: Pellerin et al. (2013), "How can a French agriculture contribute to reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures", INRA, France, 92 pages.

Figure 7. Low (L) and high (H) estimates of cost-effectiveness (EUR/tCO2e) of mitigation measures from 12 MACC studies



Notes: y- axis in log scale; N: nitrogen, AD: anaerobic digestion. See Table 27 for study references.

A range of policy approaches can be considered to encourage the uptake of mitigation measures, from education, to regulations and economic incentives —as shown in Table 25— whose relevance will depend on the social costs of mitigation measures. Several mitigation measures have a net private cost —i.e. the costs to the farmer are greater than the benefits they receive— but a net social benefit — i.e. the total benefits to the farmer and to society, including the environmental improvement, outweigh the total costs. Public policy may be needed for these socially beneficial measures to be adopted. Pannell (2008) develops a general framework based on private and public net benefits of environmental practice adoption and outlines which policy mechanism, if any, should be chosen in order to maximise the net benefits of policy intervention.

When accounting for the overall private costs, the measures in Figure 7 fall into three groups:

a) Measures where there is general agreement (if not consensus) that they have low or negative costs for which it should be possible to encourage uptake using policies focused on providing education and information: optimising N fertilisation, reducing enteric CH_4 via breeding for improved productivity/fertility; (framed by a dark rectangle in Figure 7) The case of energy efficiency improvement for mobile machinery, not present in the Figure because of an insufficient number of estimates, may also fit into this category.

b) Measures that are likely to have positive moderate costs, but would provide net benefits to society (i.e. where the cost of implementing the measure is less than the social cost of the emissions) and where an incentive-based policy approach might be justified: lowering N application below the (financially) optimal level, breeding to specifically reduce enteric CH_4 (framed by a light rectangle in Figure 7).

c) The remaining measures, that can have a wide range of cost-effectiveness values, and can reduce emissions efficiently, but would need to be carefully targeted in order to avoid undue costs.

Table 25. Examples of policy approaches to GHG mitigation

Policy approach	Types of intervention	Mitigation policy examples
Information and education	-Government-provided information and advisory services; -Labelling; -Reporting and disclosure; -Naming and shaming.	Productivity gains via public investment in agricultural R&D in the USA (see Jones et al., 2013) Provision of advice via the “Farming for a Better Climate” initiative (Scottish Government, 2013b: 147)
Self-regulation	-Codes of practice; -Co-regulation.	The Woodland Carbon Code, (Forestry Commission, 2014)
Incentive-based approaches	-Creating markets; -Tradable permits/quotas ; -Price caps; targets; -Taxes; -Rewards: tax credits, subsidies etc.	Provision of payments via the EU Rural Development Programme to restore peatlands. Provision of payments via the Conservation Reserve Program in the USA to retire sensitive cropland. (see Jones et al., 2013)
Classic regulation and its variants	This covers a wide range of statutory instruments, often backed up with sanctions, e.g.: prohibiting activities, prior permissions, standards etc.	EU Nitrates Directive – mandating nutrient application rates and timing.

Source: Adapted from MacLeod et al. (2009):11.

The two latter categories raise the question of what incentive-based policy approaches may fit better the purpose of mitigating emissions at the least cost. One way would be to impose overarching price signals (e.g. via taxes or emission permit markets) to raise the incentive for farmers to uptake mitigation measures where such measures make sense. This would also raise the incentive for innovation and the development of innovative mitigation technology and practices in agriculture. Another policy approach would be to use targeted incentive policies to support some of the most promising technical measures that are locally adapted, e.g. via voluntary payment based approaches (such as in the EU CAP).

The former may have advantages in that it does not require knowing about the local specificities. It may though face implementation and monitoring challenges. Only a few countries have adopted carbon taxation and agriculture so far remains largely outside of the scope of such policies. Recently introduced emission trading systems (ETS) in New Zealand and Korea planned to include agriculture. In New Zealand, the agriculture sector was supposed to be fully accounted for in the ETS as of 2015, but its implementation has been delayed (OECD, 2011; World Bank, 2014: 64). In Korea the 2015 ETS explicitly includes agriculture (EDF and IETA, 2013), but it is too early to assess its implementation. None of the eighteen other carbon pricing systems in place or planned at the end of 2014 explicitly accounted for agriculture (World Bank, 2014). Among other factors, the establishment of markets is difficult when facing a large number of emission sources, as in the case of agriculture. The number of emission sources also raises challenges in monitoring and verifying compliance for some measures, such as those associated with improved N use efficiency. Lastly, the role of agriculture as a provider of voluntary carbon offsets has also been discussed but not widely applied.

On the other hand, the adoption of targeted mitigation support measures can be associated with a range of potential implementation challenges. First, the question of combining measures can be difficult. A mitigation measure can be applied alone, or in combination with other measures. When applied in combination, the measures can interact, meaning that the “stand alone” abatement rate and cost-effectiveness can be quite different from the “combined” cost-effectiveness (see MacLeod et al., 2010a, Hristov et al., 2013: 121, Sikirica et al., 2014 p. 24). For example, if a farm plants legumes and decreases the amount of N fertiliser applied, then the extent to which emissions can be further reduced by improving the efficiency of N application will diminish, making N efficiency measures less cost-effective. On the other hand, optimising the soil water level via improved drainage may enhance the mitigation effect of nitrification inhibitors or make timing of nutrient applications easier. It is therefore important that any targeted policy measures take into account such synergies.

Second, production displacement effects may also need to be accounted for. Some mitigation measures can lead to significant changes in production levels (e.g. nitrification inhibitors can increase *per* ha yields, while afforestation reduces food production). Given that demand for food is projected to increase, decreasing production in one location will lead to displacement of production (and associated emissions) to other regions or countries. In order to account for this, analyses of mitigation cost-effectiveness should, in principle, calculate the emissions reduction net of any displaced emissions, although in practice such calculation can be complex and is not routinely undertaken.

Third, variability in cost effectiveness can also be problematic for policy design, especially if targeted policies are to be developed. The components of cost-effectiveness, i.e. abatement rate and costs, often show a large variation both spatially, temporally and across farm types. For example, as fertiliser and crop prices vary across years and between countries, the cost of growing more maize and less grass for animal feed might be very different for different farmers. Another example is the abatement achievable by targeting soil nitrogen fertilisation, where the GHG effect can vary with climatic regions, soil types, and weather. This variability is not accounted for in most cost-effectiveness studies, where, instead, the assumed average situation is described. Because of this, most cost-effectiveness results are guidelines rather than prescriptions applicable to individual farms or individual years. Future work could explore the different mitigation potentials and costs for different farm types and sizes. The differences in the costs and applicability of the measures due to the socio-economic context (e.g. institutions, policies, resilience of the sector) would also need to be taken into account, though global and regional cost-effectiveness studies tend to account for some of these differences.

A fourth difficulty is the uncertainty of the estimates presented in the studies, stemming from the uncertainty of the underlying data and assumptions. All of the data used in the studies have associated uncertainties. Some of the most significant uncertainties are those of the abatement rates and the estimated future uptake of the measures (Eory et al., in prep). These uncertainties are rarely quantified and presented in the analyses. Uncertainty analysis should ideally accompany cost-effectiveness studies in order to give the policy makers information about the likely range of the mitigation potential and the costs. As the complexity of models used in the studies often poses challenges to uncertainty analysis, an alternative is to conduct sensitivity analysis on the assumptions which are likely to be the most important ones.

Lastly, the non-adoption of presumed “win-win” or negative cost mitigation measures may still deserve further investigation. Measures, which engineering approaches consider having negative costs, are sometimes referred to as “win-win”, i.e. they reduce emissions while saving money. In theory, such measures should be widely adopted; however this is often not the case. Leaving aside computation errors and estimation method limitations, this creates an interesting apparent “paradox”. This paradox may result from the fact that a measure can be more expensive in practice than the studies suggest. Some significant costs, such as the transaction and learning costs of adopting measures, are difficult to quantify and therefore frequently omitted from the calculations of cost-effectiveness. Farmers’ risk aversion may also discourage them from adopting specific practices. Alternatively, it has been suggested that farmers do not necessarily adopt win-win measures because they do not act in rational profit maximising ways. Instead, their decision making is influenced by internal factors (e.g. cognition, habit and attitudes to risk), social factors (e.g. norms and roles), the policy environment, and other farm business constraints (Pike, 2008). Moran et al (2013) have gone so far as to suggest that approaches “informed by psychological and evolutionary insights, should supersede a generic win–win narrative that is a politically convenient, yet overly simplistic and potentially counterproductive, basis for mitigation policy.”

6. Main lessons: A few stand-out measures, many more with variable cost-effectiveness, and research needed on estimations and options for policy uptake

There is a large and growing body of literature on the cost-effectiveness of agricultural GHG mitigation measures, demonstrating the potential interest and opportunities they may offer. But the wide range of measures and studies makes it difficult to draw lessons from. By necessity, cost-effectiveness studies have to reduce complex biophysical and economic processes to results that can be communicated to the policy community.

Differences in the approaches used in the studies mean that some caution needs to be exercised when comparing the studies and drawing conclusions. Despite this caveat, this review shows that some measures, especially those based on improvements via fertiliser use efficiency and cattle breeding —and potentially energy efficiency improvements in mobile machinery— are consistently considered to provide highly cost-effective mitigation opportunities.

A recurring theme within the studies reviewed is that cost-effectiveness varies within, as well as between, technical options. While there are many drivers of this variation, the broader lesson that can be drawn is that in order to achieve mitigation in the most efficient way, measures should be adapted to locations and farm types to ensure the most cost-effective mitigation opportunities.

Whether their uptake should be supported via targeted programs or broader economic incentives policy remains a question of importance. Two main options are the use of sector-wide or broader economic instruments (e.g. tax or cap and trade) or the introduction of voluntary payment approaches promoting targeted measures. The first option can encourage the adoption of a range of measures based on farmer’s own constraints, but the underlying instruments can be difficult to introduce and are not currently used in agriculture. The second raises other challenges for policy design and implementation, including spatial heterogeneity of the costs and effectiveness of mitigation practices and how to adapt support to such heterogeneity. Policy makers would in particular have to be able to: (a) predict the cost effectiveness of different combinations of measures; (b) account for displacement effects; and (c) understand why farmers are sometimes reluctant to adopt apparent “win-win” mitigation measures and adapt information and advice accordingly. Finally, it should be noted that implementing mitigation measures can have positive or negative unintended effects on, for example, air quality, water quality, soil quality, biodiversity and animal health. Inclusion of these effects in the analysis could lead to significant changes in the relative cost-effectiveness of the GHG mitigation measures.

Further analysis is needed to address these challenges, and to help determine how mitigation measures may be embedded into broader climate, agricultural and environmental policy frameworks. Two upcoming OECD projects will examine in particular the synergies and trade-offs between agricultural productivity, GHG mitigation, and adaptation to climate change; and assess the barriers to adoption of potential win-win agricultural climate friendly practices.

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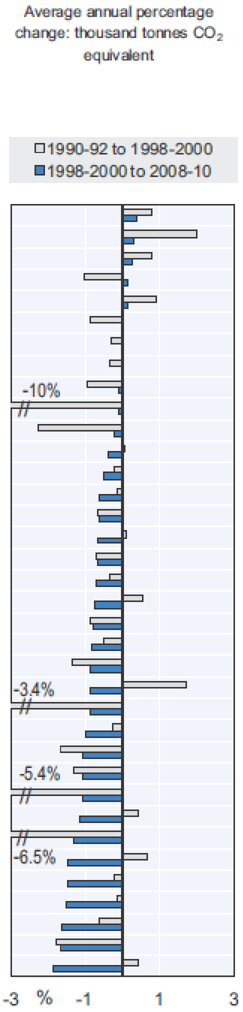
Annex A.

Trends in GHG emissions in OECD countries

Figure 8. Agricultural greenhouse gas emissions (CH_4 and N_2O) in OECD countries from 1990-2010



	Average			Change in agricultural GHG emissions[1]				Share of agriculture in national total GHG emissions	Share in total OECD agriculture GHG emissions
	Thousand tonnes, CO_2 equivalent			Thousand tonnes, CO_2 equivalent	Average annual % change	Thousand tonnes, CO_2 equivalent	Average annual % change	%	%
	1990-92	1998-2000	2008-10	1990-92 to 1998-2000		1998-2000 to 2008-10		2008-10	2008-10
Chile[2]	12 285	13 070	13 425	785	0.8	354	0.4	9	1
Canada	46 885	54 943	56 672	8 058	2.0	1 729	0.3	8	5
United States	392 450	418 180	429 546	25 731	0.8	11 366	0.3	6	36
Switzerland	6 091	5 603	5 675	-488	-1.0	72	0.1	11	0
New Zealand	30 777	33 128	33 556	2 351	0.9	429	0.1	46	3
Finland	6 222	5 809	5 823	-413	-0.9	14	0.0	8	0
Iceland	677	661	660	-16	-0.3	-1	0.0	14	0
Mexico[3]	46 739	45 486	45 424	-1 253	-0.3	-62	0.0	7	4
Israel[4,5]	2 681	2 581	2 565	-100	-0.9	-16	-0.1	3	0
Estonia	3 210	1 377	1 362	-1 833	-10.0	-15	-0.1	7	0
Poland	43 412	36 133	35 345	-7 279	-2.3	-788	-0.2	9	3
OECD	**1 220 878**	**1 226 552**	**1 182 632**	**5 674**	**0.1**	**-43 920**	**-0.4**	**8**	**100**
Slovenia	2 111	2 073	1 974	-38	-0.2	-99	-0.5	10	0
France	103 022	102 038	96 029	-985	-0.1	-6 009	-0.6	18	8
Austria	8 530	8 081	7 577	-449	-0.7	-504	-0.6	9	1
Norway	4 544	4 575	4 288	31	0.1	-287	-0.6	8	0
Germany	77 798	73 524	68 868	-4 274	-0.7	-4 656	-0.7	7	6
Luxembourg	750	730	681	-19	-0.3	-50	-0.7	6	0
Australia	86 151	89 870	83 370	3 720	0.5	-6 500	-0.7	15	7
Turkey	30 153	28 115	25 955	-2 037	-0.9	-2 160	-0.8	7	2
Sweden	8 895	8 545	7 882	-349	-0.5	-663	-0.8	12	1
Japan	31 202	27 943	25 665	-3 259	-1.4	-2 278	-0.8	2	2
Spain	37 301	42 733	39 185	5 432	1.7	-3 549	-0.9	10	3
Hungary	12 225	9 234	8 458	-2 991	-3.4	-776	-0.9	12	1
EU15	**426 951**	**417 972**	**378 073**	**-8 978**	**-0.3**	**-39 900**	**-1.0**	**10**	**32**
Denmark	12 321	10 765	9 689	-1 556	-1.7	-1 076	-1.0	15	1
Greece	11 298	10 166	9 148	-1 132	-1.3	-1 018	-1.0	7	1
Czech Republic	13 960	8 938	8 026	-5 022	-5.4	-913	-1.1	6	1
Portugal	8 138	8 430	7 521	292	0.4	-909	-1.1	10	1
Slovak Republic	6 029	3 518	3 079	-2 511	-6.5	-439	-1.3	7	0
Ireland	19 752	20 835	17 999	1 083	0.7	-2 836	-1.5	28	2
Belgium	11 763	11 555	9 967	-208	-0.2	-1 588	-1.5	8	1
Italy	41 086	40 574	34 844	-512	-0.2	-5 730	-1.5	7	3
United Kingdom	57 271	54 449	46 167	-2 822	-0.6	-8 282	-1.6	8	4
Netherlands	22 804	19 739	16 692	-3 065	-1.8	-3 046	-1.7	8	1
Korea[5]	22 349	23 152	19 514	803	0.4	-3 638	-1.9	..	2

Source: OECD (2013).

Annex B. Additional information

Table 26. Examples of the potentially ancillary costs (-) and benefits (+) that can arise from some common GHG mitigation measures

Overall effect	**+**	**+**	**+**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	
Measure	Water quality improvement due to reduced run-off	Reduced impacts from synthetic N production/ transport	Improved biodiversity	Greater land take for arable to counteract reduced yield	Increased road transport of manure/ compost	Impacts from increased production of urea, NI's etc.	Increased manure management emissions	Increased impacts of arable production	Manufacturing impacts	Public perception of product/ farming	Animal health/ welfare	Other effects
Using biological fixation to provide N inputs	x	x	x	x								
Reduce N fertiliser	x	x		x								
Improving land drainage	x											
Avoiding N excess	x	x										
Full allowance of manure N supply	x	x		x	x							
Improved timing of synthetic fertiliser N application	x	x										
Controlled release fertilisers						x						Increased N run-off risk
Nitrification inhibitors	x	x				x						
Improved timing of slurry and poultry manure application	x	x					x					
Adopting systems less reliant on inputs	x	x	x	x								
Plant varieties with improved N-use efficiency	x	x										
Separate slurry from fertiliser applications	x											
Reduced tillage / No-till	x											Reduced soil erosion
Use composts, straw-based manures in preference to slurry		x			x		x					
Higher starch concentrate diet								x			x	
Increased maize silage in diet								x				
Propionate precursors									x	x		
Probiotics									x	x		
Ionophores									x	x		
Bovine somatotropin									x	x		
Improved genetic potential for dairy cows – productivity										x	x	
Improved genetic potential for dairy cows – fertility.										x	x	
Improved genetic potential for beef cattle										x	x	
Transgenic manipulation of ruminants										x	x	

Source: Based on Moran et al., 2008, Annex B.

Table 27. Recent multiple measures studies of mitigation cost-effectiveness

Approach for cost-effectiveness calculation: 1. Bottom-up cost engineering studies; 2. Micro-economic modelling; 3.Regional/sectoral using supply-side equilibrium modes

ID	Study	Geographical scope	Resolution	On-farm or life cycle	MACC method	Interactions	Reports CE of separate measures?
1	Schneider 2000	United States	Sub-national regions	On-farm	3	Not specified	No
4	IGER 2001	United Kingdom	Farm to national	on-farm	1	Not specified	Yes
6	Graus et al. 2004	Global	World regions	On-farm	1	Yes	Yes
7	Perez 2004	EU15	NUTS2	On-farm	3	No	No
9	De Cara et al. 2005	EU15	Regional (~NUTS2)	On-farm	2	No	No
11	DeAngelo et al., 2006	Global	World regions	On-farm	1	Double-counting avoided	No
12	Hediger, 2006 and Hartmann 2007	Switzerland	Sub-national regions	On-farm	2	Not specified	No
15	Lucas et al., 2007	Global	Not specified	On-farm + other sectors	1	No	No
18	Schils et al., 2007	The Netherlands	Farm	On-farm	2	No	No
19	Schneider et al., 2007	United States	Sub-national regions	On-farm	3	No	No
20	Wassman & Pathak 2007	Philippines, China, India	Sub-national regions	On-farm	1	Not specified	No
21	Weiske et al., 2007	NW Germany	Farm	On-farm	3	Not specified	Yes
22	Amann et al., 2008	EU 27	National	On-farm	3	Double-counting avoided	Yes
23	Beach et al., 2008	Global	Global	On-farm	1	Double-counting avoided	No
24	EPA, 2008	Queensland	Queensland	On-farm	3	Yes	No
25	ICF, 2008	New Zealand	National	On-farm	1	Not specified	Yes
26	Moran et al., 2008	United Kingdom	National	On-farm	1 and 2	Yes	Yes
27	Neufeldt & Schafer, 2008	Germany	Regional	On-farm	2	Yes	No
28	Smith et al., 2008	Global	World regions	On-farm	1	Not specified	No
30	Bates et al., 2009	EU 27	EU 27	On-farm?	1	Not specified	Yes
31	Golub et al., 2009	Global	World regions	On-farm	3	No	No
32	McKinsey, 2009	Global	Global	On-farm	1	Not specified	No
33	AEA Technologies, 2010	England	National	On-farm	1	Yes	Yes
34	Durandeau et al., 2010	France	Sub-national regions	On-farm	2	Yes	No
35	Hasegawa et al., 2010	Global	World regions	On-farm	3	Yes	Yes
36	Hoglund-Isaksson et al., 2010	Kyoto Annex I countries	National	On-farm + other sectors	1	Yes	Yes
37	IBERS 2010	United Kingdom	Farm to national	On-farm	1and 2	No	Yes
38	Leip et al. 2010	EU 27	NUTS2	LCA	3	Yes	No
41	De Cara & Jayet 2011	EU 24	Regional (~NUTS2)	On-farm	2	No	No
45	Vellinga et al., 2011	The Netherlands	Farm	On-farm	2	No	Yes

ID	Study	Geographical scope	Resolution	On-farm or life cycle	MACC method	Interactions	Reports CE of separate measures?
46	Domínguez et al., 2012	EU 27	NUTS2	On-farm	3	Yes	No
47	Schulte et al., 2012	Ireland	National	LCA	1	Yes	Yes
50	van Amstel, 2012	Global	Global	On-farm	3	Yes	No
51	Wagner et al., 2012	Kyoto Annex I countries	National	On-farm + other sectors	1	Double-counting avoided	No
52	Cornet et al., 2013	Belgium	National	On-farm	1	Not specified	No
54	ICF, 2013	United States	Farm	On-farm	1	Not specified	Yes
55	Pellerin et al., 2013	France	National	On-farm, some off-farm	1	Yes	Yes
56	Reisinger & Legard, 2013	New Zealand	Farm	LCA	1	Not specified	No
57	USEPA, 2013	Global	National/supra-national	On-farm	1	Double-counting avoided	No
59	Whittle et al., 2013	Australia	Farm	On-farm	1	Double-counting avoided	No
61	Doreau et al., 2014	France	National	On-farm	1	Yes	Yes
63	Henderson et al., (in prep.)	Global	From 8 km2 to supranational	LCA	1	Double-counting avoided	No
64	Lengers et al., 2013 and Lengers et al., 2014	Germany	Farm	On-farm	2	Yes	No

Source: Cited references.

Table 28. Summary of the sub-categories of mitigation measures included in each study (for studies with cost-effectiveness calculation)

The figures indicate the number of mitigation measures within each sub-category mentioned in each study

Category / Study ID	**4**	**6**	**11**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**28**	**30**	**32**	**33**	**35**
Cropland management total	**9**	**9**	**4**	**7**	**4**	**7**	**6**	**2**	**1**	**14**	**8**	**4**	**4**	**2**	**15**
Agronomy	2	0	0	0	0	1	0	0	0	1	2	0	0	0	0
Nutrient management	7	3	2	0	3	4	3	0	1	11	2	4	1	0	6
Structural and management changes	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Tillage and residue management	0	0	0	0	0	1	1	2	0	1	1	0	1	1	1
Water and soil management	0	0	0	0	0	0	0	0	0	1	2	0	0	1	0
Rice management	0	6	2	7	0	1	2	0	0	0	1	0	2	0	8
Orchards	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grazing land management total	**0**	**1**	**0**	**0**	**1**	**0**	**1**	**1**	**3**	**1**	**4**	**3**	**0**	**0**	**0**
Grazing intensity and timing	0	1	0	0	1	0	1	0	1	0	1	2	0	0	0
Increased productivity	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Fire management	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0
Water and soil management	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Management of organic soils total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**
Restoration of degraded lands total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**3**	**0**	**1**	**0**	**0**
Livestock management	**10**	**11**	**0**	**0**	**3**	**1**	**6**	**3**	**5**	**11**	**3**	**4**	**2**	**0**	**2**
Nutrient use efficiency and feeding	3	6	0	0	3	1	4	1	1	4	1	2	0	0	0
Specific agents and dietary additives	2	1	0	0	0	0	2	1	2	3	1	0	2	0	2
Animal health	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Structural and management changes	1	2	0	0	0	0	0	0	1	0	1	1	0	0	0
Animal genetics and herd structure	4	2	0	0	0	0	0	1	1	4	0	1	0	0	0
Housing and manure total	**5**	**0**	**3**	**0**	**6**	**1**	**1**	**2**	**1**	**3**	**2**	**3**	**0**	**0**	**5**
Housing total	1	0	0	0	3	0	0	1	0	0	0	0	0	0	0
Improved manure storage and handling	3	0	0	0	2	0	0	1	0	2	1	1	0	0	2
Anaerobic digestion and CH_4 capture	1	0	3	0	1	1	1	0	1	1	1	2	0	0	3
Land use change total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**2**	**0**	**0**	**0**	**0**
Energy efficiency total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**15**	**0**
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Space heating	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0
Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
Process heating	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Electricity generation	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0
Other energy efficiency	0	0	0	0	0	0	0	0	0	0	1	0		1	0

Category / Study ID	**36**	**37**	**45**	**46**	**47**	**50**	**54**	**55**	**56**	**57**	**59**	**61**	**63**	**64**	**Total**
Cropland management total	**12**	**0**	**2**	**13**	**7**	**1**	**11**	**16**	**1**	**10**	**0**	**0**	**0**	**0**	**179**
Agronomy	1	0	0	0	1	0	1	3	0	0	0	0	0	0	13
Nutrient management	8	0	2	13	5	0	5	12	1	4	0	0	0	0	104
Structural and management changes	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Tillage and residue management	0	0	0	0	1	0	3	1	0	1	0	0	0	0	17
Water and soil management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Rice management	3	0	0	0	0	1	1	0	0	5	0	0	0	0	39
Orchards	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grazing land management total	**0**	**1**	**1**	**0**	**2**	**0**	**4**	**5**	**4**	**1**	**0**	**0**	**2**	**0**	**35**
Grazing intensity and timing	0	0	0	0	1	0	2	3	3	1	0	0	1	0	18
Increased productivity	0	1	1	0	1	0	2	2	1	0	0	0	1	0	13
Fire management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Water and soil management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Management of organic soils total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
Restoration of degraded lands total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**5**
Livestock management total	**1**	**7**	**5**	**1**	**2**	**10**	**0**	**4**	**4**	**9**	**2**	**2**	**4**	**2**	**120**
Nutrient use efficiency and feeding	1	3	2	1	0	3	0	3	0	4	1	1	2	1	52
Specific agents and dietary additives	0	4	0	0	0	4	0	1	1	5	1	1	1	0	35
Animal health	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Structural and management changes	0	0	2	0	0	1	0	0	2	0	0	0	1	1	13
Animal genetics and herd structure	0	0	1	0	2	2	0	0	1	0	0	0	0	0	20
Housing and manure total	**3**	**0**	**0**	**7**	**1**	**5**	**6**	**5**	**0**	**3**	**1**	**0**	**0**	**1**	**67**
Housing	0	0	0	2	0	0	0	0	0	0	0	0	0	1	8
Improved manure storage and handling	0	0	0	5	0	3	3	1	0	0	0	0	0	0	25
Anaerobic digestion and CH_4 capture	3	0	0	0	1	2	3	4	0	3	1	0	0	0	34
Land use change total	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**7**
Energy efficiency total	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**23**
Transport	0	0	0	0	0	0	0	1	0	0	0	0	0	0	3
Space heating	0	0	0	0	0	0	0	1	0	0	0	0	0	0	8
Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Process heating	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Electricity generation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Other energy efficiency	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3

Table 29. Number of mitigation measures in each category (bold) and sub-category (italic)

Categories and sub-categories	Number of measures
Cropland management total	**64**
Agronomy total	7
Nutrient management total	32
Longer term structural and management changes	2
Tillage and residue management total	6
Water and soil management total	2
Rice management total	15
Grazing land management total	**16**
Grazing intensity and timing total	7
Increased productivity total	8
Water and soil management total	1
Management of organic soils total	**1**
Restoration of degraded lands total	**4**
In general	1
Nutrient amendments	1
Organic amendments (manures, biosolids, composts, etc.)	1
Reducing tillage	1
Livestock management total	**49**
Nutrient use efficiency and feeding total	17
Specific agents and dietary additives total	22
Animal breeding, genetics and herd structure total	10
Housing and manure total	**24**
Housing total	7
Improved manure storage and handling total	12
Anaerobic digestion and CH_4 capture total	5
Land use change total	**7**
Shelter belts/riparian zones/buffer strips	1
Arable to grassland	1
Afforestation	1
Avoid conversion of woodlands	1
Biomass crops	1
Sylvopastoral	1
Other	1
Energy efficiency total	**16**
Transport total	1
Space heating total	7
Electricity total	3
Process heating total	1
Electricity generation total	4

Table 30. Number of times each mitigation measure was included in the reviewed studies

Category / Mitigation activity	TOTAL
Cropland management total	**179**
Agronomy total	**13**
Improved crop varieties	2
Extending the perennial phase of crop rotations	0
Reducing bare fallow	1
Adding nutrients when deficient	0
Adopting systems less reliant on inputs (nutrients, pesticides etc.)	1
Catch/cover crops (vineyards/orchards as well)	5
Keep pH at an optimum for plant growth (e.g. liming)	0
Changing from winter to spring cultivars	0
Agroforestry (with low tree density)	2
Hedges	1
Cultivated crops to increase soil C (e.g. deep-rooted or permanent plants)	0
Increase production optimising production factors to increase soil C	0
Other agronomy	1
Nutrient management total	**104**
Precision farming	4
Avoiding N excess (adjusting yield targets)	6
Use a fertiliser recommendation system	1
Analyse manure prior to application	1
Full allowance of manure N supply	4
Improved timing of mineral fertiliser N application (weather-related timing)	3
Delay the first fertiliser application in the spring	1
Split fertilisation (baseline amount of N fertilizer but divided into three smaller increments)	4
Use the right form of mineral N fertiliser	2
Improved timing of slurry and poultry manure application (weather-related timing)	3
Improved timing of manure application (more storage)	2
More spring and less summer manure application	2
Do not apply fertiliser at high-risk areas	0
Separate slurry applications from fertiliser applications by several days	1
Use composts, straw-based manures in preference to slurry	1
Mix nitrogen rich crop residues with other residues of higher C:N ratio	0
Placing N precisely in soil	6
Trailing hose - recommended on arable and grassland	3
Trailing shoe - recommended mainly on grassland	4
Injection - recommended mainly on grassland	4
Incorporate manure after application	4
Low trajectory slurry application	2
Increasing rate of infiltration into soil (dilution of manure, application of water after spreading)	0
Controlled release fertilisers	2
Nitrification inhibitors	13
Production of natural nitrification inhibitors by plants	0
Application of urease inhibitor	0
Keep pH above 6.5	0

Category / Mitigation activity	TOTAL
Plant varieties with improved N-use efficiency	1
Genetically improve the efficacy of nitrogen uptake and use by plants	1
Biological N fixation (legumes in rotations)	4
Reduce N fertiliser	11
Applying organic input on cropland instead of on grassland	0
Improved maintenance of fertiliser spreaders	3
Modify soil microbial communities to reduce N2O into N2 (e.g. incorporation of Rhizobia strains)	0
Fertiliser free zone on filed edges	4
Optimisation of fertiliser distribution geometry	1
Water buffer strips	1
Reduce liming	1
Other nutrient management	4
Structural and management changes total	**2**
Tightening the N cycles (regionally optimised plant and animal production)	1
Relo13+20cate high N-input cropping to drier, cooler areas	0
Less monoculture	1
Other	0
Tillage and residue management total	**17**
Reduced tillage	6
No-till	5
Retain crop residues	1
Avoid no-tillage, consider occasional deep ploughing	0
Plough in early spring, spread crop residues evenly and control compaction	0
Avoid burning of residues	2
Burying biochar	0
Controlled traffic	1
Other	2
Water and soil management total	**4**
Improved irrigation	2
Land drainage	2
Loosen compacted soils / Prevent soil compaction	0
Prevent soil erosion	0
Other water and soil management	0
Rice management total	**39**
NA	0
Aeration of rice-growing soil (e.g. reduce the depth of paddy fields, empty them several times p.a.)	4
Shallow flooding	2
Mid-season drainage	5
Off-season straw	2
Alternate flooding	4
Rice straw compost	2
Phosphogypsum	3
Direct wet seeding	4
Replace urea with AN	1
Replace urea with ammonia bicarbonate with ammonia sulphate	2
Changing fertiliser type (in general)	1
Other uses of rice straw	1

Category / Mitigation activity	TOTAL
Low methane cultivars	3
Continuous flooding	1
Other rice	4
Orchards total	**0**
Convert to trellis system	0
Other	0
Grazing land management total	**34**
Grazing intensity and timing total	**18**
Reduce N on the most intensive permanent and temporary grasslands	3
Increase stocking density on medium productivity grassland	2
Intensive grazing (cattle are frequently rotated between pastures)	4
Extended grazing season	2
Take stock off from wet ground	2
Reduce stocking density	1
Other	4
Increased productivity total	**13**
Fertilization	1
Pasture renovation	0
Avoid fertiliser applications prior to pasture renovation	0
Biological N fixation (grass-legume mixtures)	5
Species introduction (including legumes)	0
New forage plant varieties for improved nutritional characteristics	0
New forage plant varieties to buffer grass growth	0
Increasing digestibility (forage quality)	0
Corn silage replacing grass silage	0
More legume silages and less grass silages	0
Higher sugar content grasses	2
Other	2
Increase the lifespan of temporary grassland	1
Increased pasture productivity	1
Improved irrigation	1
Fire management total	**2**
Fire management	2
Water and soil management total	**1**
Adjust pH to more than 5 by liming	1
Land drainage - SEE AT CROPLAND MGMT	0
Prevent soil compaction - SEE AT CROPLAND MGMT	0
Management of organic soils total	**2**
Avoid drainage of wetlands / conversion of peatlands	1
Avoiding row crops and tubers	0
Avoiding deep ploughing	0
Maintaining a shallower water table - peat	0
Maintaining a shallower water table - arable	0
Other	1

Category / Mitigation activity	TOTAL
Restoration of degraded lands total	**5**
In general	1
Erosion control	0
Revegetation	0
Nutrient amendments	1
Organic amendments (manures, biosolids, composts, etc.)	1
Reducing tillage	1
Retaining crop-residues	0
Conserving water	0
Other	1
Livestock management total	**120**
Nutrient use efficiency and feeding total	**52**
Feeding more concentrates (replacing forages)	8
Target specific livestock nutrient requirements	2
High fat diet (dietary lipids)	10
Balance diet for energy and protein (e.g. reducing protein, increasing carbohydrates)	6
High starch diet	3
High starch (maize) diet	5
Increase protein quality (balanced essential amino-acid composition)	0
Optimise (=reduce) protein intake - cattle	1
Reduce protein intake (without AA supplementation)	0
Reduce protein intake and provide AA supplementation	1
High quality oats	1
Increased milking frequency	0
Bovine somatotropin	5
Estimating potential CH4 production from feeds	0
Feed procession	0
Mechanical treatment of feed	0
Chemical treatment of low quality feedstuffs	1
Feeding total mixed ration	0
Precision feeding (+ feed analysis)	0
(Multi)Phase feeding	1
Improved feed conversion (increasing energy content and digestibility)	1
Continuing conventional dietary improvement	0
Improved diets for pigs	0
Reduce the deposition of excess subcutaneous fat in beef and lambs as they near slaughter weight	0
Increase body fat at slaughter	1
Food industry co-products as feed	1
Home-grown feed	0
Other	2
Improved feed intake	3
Specific agents and dietary additives total	**35**
In general	4
Higher salt content of the diet	0
Plant extracts	0
Essential oils	1
Tannins	1

Category / Mitigation activity	**TOTAL**
Saponins	0
Ionophores (e.g. monensin)	3
Antibiotics	2
Propionate precursors	6
Nitrate	4
Nitrification inhibitors fed directly	0
Hexose partitioning	1
Directly fed probiotic microbes (e.g. yeast products)	4
Manipulation of rumen archaea and bacteria	1
Directly fed microbes - acetogens, methane oxidisers	0
Promoting acetogens	0
Antimethanogens	2
Immunogenic approaches to eliminate methanogens	0
Genetic modification of rumen microflora	0
Vaccination against methanogens	3
Alternative hydrogen acceptors (e.g. unsaturated fatty acids)	0
Halogenated methane analogues	0
Defaunating agents	0
Naturally occurring plant compounds (new species/GM)	0
Chicory	0
Use of exogenous enzymes	0
Allicin	1
Glycerol	1
Other	1
Animal health total	0
Better health planning	0
Improve hygiene & supervision at lambing	0
Improve ewe nutrition in late gestation to increase lamb survival	0
Vaccination	0
Anti-parasitics	0
Other	0
Structural and management changes total	**13**
Reduction in the number of replacement heifers / Improved fertility management	2
Multi use of cows (milk, calves and meat)	0
More feed production on farm scale or local level	0
Organic farming	0
Winter management of cattle (collected and re-utilised excreta)	0
Increase of grazing in comparison to housing	1
Increase of housing in comparison to grazing	1
Reduce stocking rates	6
Skipping the stocker phase	1
Other	2
Animal breeding, genetics and herd structure total	**20**
Selection for reduced methane production	5
Selection for longevity , fertility, and other non-productive traits	1
Selection for higher yield / weight gain	3

Category / Mitigation activity	TOTAL
Selection for lower CH4 emissions (residual feed intake)	0
Improved milk yield by 30% - dairy	0
Improved milk yield	2
Improved feed conversion efficiency	0
Cloning	0
GM livestock	0
Artificial insemination	0
Planned selection of male/female at insemination (embryo and sperm sexing)	0
Twinning	0
Transgenic manipulation	2
Improved genetic potential in general	3
Improved genetic potential - productivity	1
Improved genetic potential - fertility	1
Improved genetic potential - longevity	0
Use bulls with a high PLI or Profitable Lifetime Index when breeding dairy cows	1
Use bulls/rams with a high EBV or Estimated Breeding Value when breeding beef cattle/lamb	0
Use cows with lower yield but which can produce beef calves	0
Develop mixed breeds or industrial cross-breeding	0
Switching breeds	0
Other	1
Housing and manure total	**67**
Housing total	**8**
New low-emission livestock and poultry housing systems	1
Natural ventilation	0
Decreasing of air velocity above manure	0
Cooling the manure covered surfaces	0
Filtration of animal house emissions	1
Tied systems instead of loose-housing systems	0
Slurry-based systems - dairy	1
Straw-based systems - dairy	1
Loose-housing, deep litter stalls - dairy	0
Cages and aviaries instead of floor systems for layer hens	0
Keeping surfaces, manure and animals dry	0
Improved drinking systems	0
Drying of manure (esp. poultry)	0
Absorption of urine / Use of bedding material	0
Straw-based systems	0
Deep litter systems	0
Deep litter systems - pigs	0
Slurry-based systems / Deep dung channels	0
Partly or fully slatted floors	0
Frequent manure removal to outside (cooler) storage	1
Type of stable	1
Other	2
Improved manure storage and handling total	**25**
Cooling	1
Slowing down anaerobic decomposition by removing slurry to an outdoor storage - pigs	0

Category / Mitigation activity	**TOTAL**
Decreasing the airflow across slurry and FYM	0
Covering manure heaps	0
Lowering the filling level of slurry storage	0
Covering slurry (e.g. oil, plastic, straw, granulates, rigid cover)	7
Semi-permeable	1
Impermeable	2
Allowing the build-up of natural crust on cattle slurry	2
Separating solids from slurry	1
Rapid separation of faeces and urine	0
Composting solid manure (also after slurry separation)	0
Switch from solid manure to slurry (anaerobic) system	1
Switch from anaerobic to aerobic facilities	2
Controlled aeration during slurry storage	0
Minimising of stirring slurry	0
Manure acidification	0
Reducing the surface per unit volume of slurry or FYM (e.g. tanks instead of lagoons)	0
Combustion of poultry litter	0
Controlled denitrification processes in slurry	0
Increasing the carbon content of the manure (adding straw)	1
Compaction of FYM	0
Comminution of FYM	0
Increased frequency of slurry spreading	0
In-house poultry manure drying	0
Incinerate poultry litter	1
Daily spread of manure	2
Other	4
Anaerobic digestion and CH4 capture total	**34**
AD	18
Centralised AD	3
On-farm AD	4
Methanisation, methane capture and combustion	6
Methane capture with flaring (no energy produced)	0
Produce H2 from manure using an anaerobic process and convert it into energy	0
Other	1
Land use change total	**7**
Shelter belts/riparian zones/buffer strips	1
Arable to grassland	1
Arable to woodland	0
Arable to set-aside	0
Grassland to woodland	0
Drained croplands - wetlands	0
Afforestation	1
Permanent revegetation of set-aside	0
Restoration of peatlands	0
Avoid conversion of woodlands	1
Biomass crops	1
Sylvopastoral	1
Other	1

Category / Mitigation activity	TOTAL
Energy efficiency total	**23**
Transport total	**3**
Increased fuel efficiency in tractors, etc.	3
Service and maintain vehicles (incl. tyre pressure, lubricant levels, etc.)	0
Ensure employees use fuel saving driving techniques	0
Other transport	0
Space heating total	**8**
Micro-CHP	1
Increased heating efficiency (livestock houses and greenhouses)	2
Fit automatic door closers, strip curtains, draught strips	1
Use windbreaks to protect against high winds	0
Improve insulation (roof spaces, walls, hot internal and external pipes)	1
Improve heating (install time and temperature controls, separate thermostats for heating and ventilation)	1
Maintain and check thermostats regularly	0
Recirculate warm air in tall farm buildings	0
Minimise ventilation especially when heating is on	0
Use outside air for cooling whenever possible	0
Regular checks on ventilation (clean up, service)	0
Fit variable-speed ventilation	0
Service boilers regularly	0
Move heated greenhouses to areas where the can utilise waste heat	0
Clean greenhouse glass regularly to utilise solar heating better	0
Install thermal screens in greenhouses	1
Replace broken or slipped glass	0
Other space heating	1
Waste total	**0**
Reduce waste during transport, processing and storage	0
Other waste	0
Electricity total	**3**
Pre-cooling milk by using a ‘water to milk’ plate cooler	1
Efficient refrigeration (away from heat sources, regular defrosting, servicing)	1
Other milk	0
Use fluorescent light bulbs	0
Use more efficient fluorescent tubes	0
Other lighting	1
Reduce pressure washing time by pre-soaking	0
Other	0
Process heating total	**1**
Improved crop-drying	1
Maintain and clean your crop dryers regularly	0
Use humidity sensors for crop drying	0
Time drying to make most use of less humid periods in the year	0
Other process heating	0
Electricity generation total	**5**
Use of renewable electricity	0
Biomass combustion	3
Solar energy	1

Category / Mitigation activity	**TOTAL**
Wind power	0
Solar water heating	0
Small-scale hydro-electric power	0
Ground-source or air-source heat pumps	1
Other electricity generation	0
Other energy efficiency	3