Farm-Level Assessments of Greenhouse Gas Marginal Abatement Cost Curve Emissions: Understanding the Implications of Interactions and Heterogeneity

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Abstract

Mitigation of climate change remains a central focus of the EU; with it's 2030 Climate Target Plan, the Commission proposes to raise the EU's ambition on reducing greenhouse gas emissions (GHG) to at least 55% below 1990 levels by 2030. In Ireland, GHG emissions from the agricultural sector are high compared to other developed countries at 37.1% of total greenhouse gas emissions (GHG). Extensive efforts have been brought to bear on the development and evaluation of mitigation measures that reduce greenhouse gases from the agricultural sector. However, the extent to which mitigation measures reduce GHG emissions at the farm level has received less attention, most especially the implications of farm heterogeneity on optimal emission reduction. Using EU Farm Accountancy Data Network data for the Republic of Ireland in 2020, this study uses Marginal Abatement Cost Curve (MACC) analysis to assess a suite of GHG mitigation measures and accounts for interaction and heterogeneous effects across 5 different farm system types. The result of the study shows that crude protein in animal diets is the most cost-effective measure for all the farm systems. While liming and protected urea are cost-effective measures for all the farm systems on the other hand some measures fluctuate in their categorisation. The findings show that no two MACC curves across farm systems are the same, that is the rankings of measures change from one farm system to the other. The combination of mitigation measures to reduce GHG emissions may not necessarily yield a cost-effective outcome.

Keywords: climate change, mitigation, GHG, farm-level, heterogeneity.

1.0 Introduction

Globally, climatic change continues at pace as a result of increased greenhouse gas (GHG) emissions into the atmosphere (DCCAE., 2019). These changes manifest in the form of increased temperature, alterations in rainfall durations & intensities, and increased heat and sunshine duration among other climate parameters. The alterations in these climate parameters may in turn lead to reduced crop production, and livestock population, while also affecting both animal and human health (Darwin, 2004; El-Sayed & Kamel, 2020). In Ireland, this may take the form of reduced forage and livestock production, reduced grass production and changes in grazing patterns (Holden & Brereton, 2002; Ljungqvist et al., 2021). Increased

GHG emissions in Ireland have also led to climatic shocks in the form of droughts, floods and extreme snowfall (DCCAE., 2019).

The agricultural sector is a significant contributor to GHG emissions globally. Moreover, the proportion of agriculture's contribution to global GHG emissions has continued to increase from about 12% of global emissions in 2012 (Hosonuma et al., 2012; Tubiello et al., 2015) to 17% in 2018 (FAO., 2020) and 20% in 2019 and 2020 (Ahmed et al., 2020; FAO., 2021, 2022). In the European Union (EU), agriculture accounts for approximately 10% of the total GHG emissions (EEA, 2019). However, in 2021 the agricultural sector accounted for 37.5% of national GHG emissions in Ireland and this sector was the single largest contributor to GHG emissions (EPA., 2021).

Under the Paris Agreement, The agricultural sector is required to reduce its GHG emissions in the context of Ireland's commitment to reduce national GHG emissions and achieve climate neutrality by 2050. The agreement posits that the EU has a 55% reduction target of GHG emissions in 2030 relative to the 1990 scenario (DCCAE, 2023), these target levels are trickled down to individual countries in the EU. For Ireland, this implies a 51% reduction level in GHG emissions compared to 2018 to be achieved by the 2030 commitment period (EPA, 2022; DCCAE, 2023). The Climate Action Plan 2021 of Ireland sought a 25% emissions reduction target for agriculture, which implies a reduction in emissions from 20.03 metric tonnes of carbon dioxide equivalence (Mt CO_2e) in 2018 to between 16 and 18 Mt CO_2e by 2030 (DCCAE, 2021, 2023).

Reducing GHG emissions would contribute to achieving sustainable food production which is the central aim of many national and global communities. This is a central aim of the EU Farm to Fork Strategy which seeks to ensure sustainable food production and consumption, ensure food security, avoid food losses and wastage and ensure the efficient movement of food along the value chain system (EU., 2020). Thus, to ensure sustainable food production across the different farm systems, there is an urgent necessity to critically assess the optimal abatement of these negative GHG emissions across different farm types while trying to minimize any adverse impacts on food production.

While several studies exist on the assessment of the abatement of GHG emissions in Ireland and the global community at large at an aggregate scale, very few studies (Jones et al., 2015) have considered assessing the importance of farm heterogeneity and interactions amongst abatement measures, this study hypothesises that the "one type fits all" approach to assessing MACC is not optimal for policy design. Thus, building on the previous works by Lanigan et al. (2018); Buckley et al. (2020) and Ogunpaimo et al. (2022), this study seeks to: (i) assess the abatement potential, cost and cost-effectiveness of a suite of GHG mitigation measures; (ii) used the Marginal Abatement Cost Curve (MACC) based methodology to explore the effect of farm system heterogeneity of different GHG based mitigation measures ; and (iii) examine interactions in the effects of the abatement measures.

This article is structured as follows Section 2 illustrates and describes the conceptual framework of the GHG emission flow. Section 3 explains the methodology, Section 4 presents the results and Section 5 discusses the findings and concludes.

2.0 Empirical Framework

There is a body of literature that assesses the cost-effectiveness of mainly GHG mitigation options. Moran et al. (2011) addressed the procedures and challenge of constructing a 'bottom-up' marginal abatement cost curve (MACC) for GHG emissions from UK agriculture. Their results indicated a higher proportion of GHG emissions (5.38 Mt CO_2e) can be abated by the implementation of cost-beneficial, cost-neutral and cost-effective measures.

Eory et al. (2018a) emphasized addressing and accounting for interactions of mitigation measures, while Eory et al. (2018b) reported on the importance of accounting for uncertainties in constructing a bottom-up GHG MACC on a standalone and combined basis. Their results indicate that while most measures are cost-effective under some scenarios, other measures may be too expensive to adopt under certain scenarios. In a similar vein, this study would account for interactions amongst the mitigation measures while using a bottom-up approach to GHG MACC.

Pexas et al. (2020) adopted a bottom-up approach to account for the marginal abatement cost of abatement measures in a European pig production system. Slurry removal was identified as an important mitigation measure, with measures accounted for on a standalone and combined basis. The results showed that measures range from cost-beneficial measures to cost-ineffective measures, their result showed the presence of interaction effects among abatement measures under different scenarios

In the Republic of Ireland, Schulte and Donnellan (2012); O'Brien et al. (2014) and Lanigan et al. (2018) produced MACC curves for GHG emissions emanating from agricultural sources, Donnellan and Hanrahan (2011) produced a report that evaluated Greenhouse Gas Emissions by Irish Agriculture as a consequence of the Food Harvest targets. This body of literature has used a top-down national aggregate scale approach to the evaluation of measures.

The report by Schulte and Donnellan (2012) gave an overview of the amount of GHG gases that can be abated using the Life Cycle Assessment (LCA) and the Intergovernmental Panel on Climate Change for National Inventories (IPCC-NI) methodology in Irish agriculture. The abatement potential of the LCA methodology was 0.7Mt CO_2e higher than the IPCC approach. The result also indicated a difference in the rankings of mitigation measures between the two methodologies. Furthermore, O'Brien et al. (2014) noted that suggesting the adoption of some abatement measures to farmers may be quite problematic mainly due to the contradiction in the positions of abatement options by the LCA and IPCC National Inventory-based MACC methodologies.

The report by Lanigan et al. (2018) builds on the work of Schulte and Donnellan (2012) by using the FAPRI-IRELAND MODEL to project future activity data levels. Some of the abatement options studied include 27 abatement measures ranging from agricultural, land-use and energy-based mitigation measures.

3. Methodology

The IPCC approach is a popular approach used to estimate GHG emissions especially when it concerns meeting national targets; it calculates the GHG emissions as those emanating from the production, consumption and exportation of goods from the geographical location of a country but does not account for those emissions that occur during the production of imported inputs (O'Brien et al., 2014). An alternative to the IPCC approach is the Lifecycle Approach (LCA), this approach considers all the GHG emissions from the raw materials, through the value chain to final disposal (ISO, 2006). Based on the nature and availability of data, this study adopts the IPCC approach in calculating the total GHG emissions from each farm.

The IPCC framework identifies nine categories of activity that contribute to agricultural GHG emissions. These include enteric fermentation, manure management, rice cultivation, agricultural soils, prescribed burning of savannahs, field burning of agricultural residues, liming, urea application, other carbon-containing fertilisers and others (EPA., 2021).

While the aforementioned activities are adopted as the GHG emissions category when calculating Irish agriculture's GHG emission profile as in the case of Lanigan et al. (2018), this study only focused on four categories. This study assesses the abatement of farm-level GHG across different farm systems to explore the effect of heterogeneity. The activities under which the abatement of GHG emissions will be accounted for in this study fall under (i) manure management (ii) agricultural soils (iii) liming and (iv) Urea application. This study focused on 4 categories as against the 9 categories in the IPCC framework for agriculture. The justification for concentrating on the 4 categories is that these are the activities applicable to Irish agriculture and measurable at the farm scale.

3.1 Data

The analysis of the data is based on the IPCC-based national inventory accounting methodology (as implemented by the Environmental Protection Agency in Ireland) where the total GHG emissions across the aforementioned farm activities (i.e. manure management, agricultural soils, liming and urea application) are estimated by multiplying the farm's activity data with the emission factor of a particular activity shown in equation (1) below.

$$Total\ GHG = \sum_{i=1}^{n}(Activity\ data * Emission\ factor) \quad (1)$$

Data on emission factors were obtained from the Irish National Inventory Report (EPA, 2020), and farm-level activity data were obtained from the Irish Agricultural and Food Development Authority (Teagasc) National Farm Survey (NFS) 2020 dataset which is part of the European Union (EU) Farm Accountancy Data Network (FADN). The Teagasc NFS data involves an annual random nationally representative sample dataset collected since 1972 on farms' outputs, income and cost in addition to farm household characteristics and environmental issues (Teagasc, 2017a).

In this study farms are categorised as dairy, cattle, sheep, tillage and mixed livestock. However, it is noteworthy that the farm types only represent the dominant enterprise and that these farms can have multiple enterprises. Table 1 shows the individual farms' profile and their description.

Table 1. Farms Profile from NFS 2020 Data

Farm Type	Parameter				
	Description	**Farm size (ha^{-1})**	**Livestock Units**	**Sample size**	**Sample size (Weighted to population)**
Specialist Dairying	Dominant enterprise is milk production	60.8	139.4	290	16146
Cattle	Involves both Cattle Rearing and Cattle Other systems of production	33.9	54	341	54020
Sheep	Dominant enterprise is sheep	44.3	68.5	108	14322
Tillage	Dominant enterprise is cereals or root crops	61.2	41.4	59	6879
Mixed Livestock	Some combination of grazing livestock (dairy, cattle, sheep) or grazing livestock combined with a crop enterprise. Dairying tends to be the main livestock enterprise.	64.4	159.8	14	1877
Total		42.6	86.2	812	93244

Source: Ogunpaimo et al. (2022)

3.2 Bottom-Up Marginal Abatement Cost Curve (MACC) Methodology

The MACC methodology involves estimating an incremental cost of the alternative abatement measures relative to a baseline scenario. This is then divided by the emission reduction (AP) obtained by to obtain the cost-effectiveness of implementing a mitigation measure (CE) (Moran et al., 2011; Schwarz et al., 2013;

Dequiedt & Moran, 2015; Lanigan et al., 2015; Lanigan et al., 2018). Following Moran et al. (2008) and Bockel et al. (2012) the following methodological steps fare followed to develop a bottom-up MACC for the assessment of mitigation measures at the farm scale.

i. Select the abatement options to appraise.
ii. Identify the baseline abatement emission scenario for each farm.
iii. Assess the abatement potential (volume of abatement) of different scenarios and take into account the adoption rate of the mitigation actions.
iv. Identify and quantify the costs and benefits.
v. Calculate the 'stand-alone' Cost-effectiveness (CE) and abatement potential (AP) of each measure (i.e. if measures do not interact) to generate 'stand-alone' MACCS;

$$CE = \frac{Cost\ of\ Abatement}{AP\ (tC0_2e\ avoided)} \tag{2}$$

Where

CE= Stand-alone cost-effectiveness measured as € per $tC0_2e$ abated

$Cost\ of\ Abatement = \left(Cost_{with\ mitigation} - Cost_{baseline}\right) * D$

D=discount factor

AP=Abatement potential

$$AP = AR * \rho \tag{3}$$

Where

AR = Adoption rate

ρ = additional land area of farm land or livestock number of livestock units(over and above the baseline land area or animal numbers) that the measure could be applied to in the given period.

Following the estimation of cost-effectiveness and abatement potential on a standalone basis. Estimates are then recalculated accounting for any interactions between measures to produce 'Combined' MACC results. (Moran et al., 2008). Following Webb et al. (2005) we assume that mitigation measures are not independent thus the abatement potential of the combined measure are simply not additive because a reduction of GHG emissions at one stage of the farm activities (e.g agricultural soils) may lead to further reduction of GHG emissions down the chain (e.g urea application) .

3.2.1 Rationale for the Selection of Abatement Measures

Following Lanigan et al. (2018); the abatement measures considered in this study include:

1. **Protected Urea:** The use of nitrogen fertilisers to achieve increased crop and livestock production is quite popular in Europe, specifically the use of calcium ammonium nitrate (CAN) fertiliser dominates all other nitrogen fertilisers in western Europe (Tzemi & Breen, 2019). However, the use of CAN fertiliser contributes higher levels of atmospheric N_2O than urea, the replacement of CAN fertiliser by protected urea has been reported to reduce N_2O emissions and also save cost (Harty et al., 2016). The rationale behind using protected urea which is in form of urea fertilizer treated with N-(n-butyl) thiophosphoric triamide (NBPT) is evident in past studies that found that protected urea resulted in lower GHG emissions (Abalos et al., 2012; Nkwonta et al., 2021; Bobrowski et al., 2021; Krol et al., 2020) and increase nitrogen uptake.
2. **Liming:** The application of lime on acidic soils (characteristics of most of the Irish soils) increases soil pH and contributes to the plant's absorption of nutrients, minimizes the spread of plant diseases, forms better soil moisture, soil structure and aeration for plants (Nadeem et al., 2020). Controversies exist on the implication of liming on GHG emissions. Some studies have indicated that liming reduces the need for inorganic fertilizers and consequently N_2O emissions (García-Marco et al., 2016; Lanigan et al., 2018; Barton et al., 2013) however, liming increases the direct emissions of CO_2 (Kunhikrishnan et al., 2016). The net effect of the measure hence needs to be assessed. The application of lime was ranked as one of the most effective abatement measures for both Irish (Lanigan et al., 2018) and Scottish agriculture (Eory et al., 2021).
3. **Clover:** Extensive literature (Spink et al., 2019; Buckley et al., 2020; Eory et al., 2020) exists on using clover as a mitigation strategy for GHG emissions. The importance of using clover as an abatement practice can be attributed to its natural fixation of nitrogen which reduces the need for chemical fertilization, thus reducing emissions from chemical fertilizer (Yan et al., 2013; Buckley et al., 2020; Eory et al., 2020; Harris & Ratnieks, 2021). Spink et al. (2019) affirmed that an inverse relationship exists between GHG emissions and biologically fixed nitrogen from the use of white clover. On the other hand, Yan et al. (2013) reported that the use of white clover reduces N_2O and CO_2 but has no effect on CH_4 emissions.
4. **Low Emission Slurry Spreading (LESS):** The most common method of applying liquid-based animal manure (slurry) is the use of a splash plate. This method broadcasts the slurry over a wide area. Alternative application methods exist under the broad label of Low Emission Slurry Spreading techniques (LESS). LESS consists of the use of slurry injection, trailing hose and trailing shoe. These techniques reduce NH_3 emissions (an indirect greenhouse gas) compared to the use of a splash plate.

   LESS is based on the principle of reducing the area of the ammonia emitting surface, in this case of soil/plant surface that is covered by the applied liquid manure and can reduce ammonia emissions by more than 50% when compared to emissions associated with the use of splash plate methods (Thorman et al., 2008; Buckley et al., 2020). The trailing hose reduces the ammonia volatilisation surface area by depositing slurry on top of the grass in bands rather than broadcasting over a larger surface area, while the trailing shoe application reduces the ammonia volatilising surface area by depositing slurry on the soil surface, underneath the grass.

Thus, the reduction in NH_3 leads to an indirect reduction in N_2O emissions during slurry spreading (Lanigan et al., 2018). The use of the LESS method as a mitigation option is an accepted mitigation practice across developed countries (Wagner et al., 2017).

5. **Covering of Slurry Stores:** Some studies have applied the use of slurry covers to abate ammonia emissions, they reported that the covering of slurry led to a significant reduction of NH_3 emissions (Zhang et al., 2019; Buckley et al., 2020) and GHG emissions (Eory et al., 2020). NH_3 reduction at the slurry storage stage leads to higher nitrogen retention in the farm system. This in turn reduces the requirement for chemical N fertiliser for a given level of agricultural production.
6. **Slurry Amendments:** The emissions of GHG during slurry storage require the need for slurry amendments to be included as corroborated by previous studies (Kavanagh et al., 2019). These amendments may include alum, ferric acid, sulphuric acid and acidic acids. Kupper et al., (2020) argued that previous works of slurry amendment led to a reduction of CH_4 during storage and an increase in N_2O emissions while Lanigan et al. (2018) posited that the use of slurry amendment led to a reduction in both CH_4 and N_2O emissions.
7. **Crude protein in diets:** The control of crude protein in dairy and pig diets is evidenced by the previous report such as (Sajeev et al., 2018a; Buckley et al., 2020) that worked on NH3 and GHG abatement in Ireland, Europe and the global community at large. Crude protein in diets works by lowering the proportion of in urine and that excreted thus leading to a reduction in NH_3 and N_2O emissions among other nitrogen emissions (Chadwick et al., 2011; Külling et al., 2002; Abbasi et al., 2018).

3.2.2 Assumptions for the Selection of Abatement Measures

The assumptions underpinning the selection of the abatement measures are shown in Table 2. The assumptions here follow closely that of Ogunpaimo et al. (2022), however, it is noteworthy that the assumptions for the GHG abatement potentials indicated in Table 1 are in addition to those made for the NH_3 abatement in Ogunpaimo et al. (2022), while the cost-assumptions are relatively the same.

Table 2: Assumptions Applied to Modelling Mitigation

Abatement Measure	Intervention	Abatement Potential Assumptions	Cost Assumptions	References
FERTILISER MEASURES				
Protected Urea	Replacement of CAN, straight urea and 50% of nitrogen fertilizers to protected urea	The mitigation potential was assessed using the Tier 2 IPCC calculation methodology (IPCC 2014b) and therefore includes the calculation of N_2O emissions from indirect sources and CO_2 emissions from urea use.	Cost per kg of Straight urea = € 0.73 and CAN=0.87 (Irish Central Statistics Office (2021)). The market price of protected urea was assumed to be € 0.8 based on prevailing market conditions at the time.	Abalos et al. (2012) Schraml et al. (2016) CSO (2021) Ogunpaimo et al. (2022) Lanigan et al. (2018) Ogunpaimo et al. (2022)
Liming - The application of lime on soils with a sub-optimal pH .	The Teagasc 2019 soil analysis revealed that 46% of the dairy farm area, 50% of the cattle and sheep farm area and 12% of tillage farm area have sub-optimal soil pH (<6.2). 22%, 19% and 5% of dairy farm area have a soil pH of 5.9-6.2, 5.5-5.9 and <5.5 respectively. 1%, 9% and 12% of tillage farms have a soil pH of 5.9-6.2, 5.5-5.9 and <5.5 respectively. 8%, 21% and 21% of cattle and sheep farms have a soil pH of 5.9-6.2, 5.5-5.9 and <5.5 respectively.	This research assumes that all sub-optimal soils are treated with lime. Nitrogen use efficiency (NUE) is based on the replacement of chemical N of liming and protected urea. By raising the soil pH to 6.2, the nitrogen fertilizer requirement is reduced Using the Teagasc long-term soil experiments the pH response rate is 1 t/ha =0.15 pH units for mineral soils (i.e soil pH<5.5) and 1 t/ha =0.2 pH units for soils with pH between 5.5-6.2. The soil pH and the pH response rate were used to estimate the quantity of lime required for each category of soil sub-optimality and across different farm types. 80kg of N/ha was assumed to be released from liming thus reducing the need for chemical fertilizer application.	In line with recommended guidelines (Teagasc, 2020) a soil sample is assumed to be taken for every 3 hectares of land targeted under this pathway at a cost of €25 per sample to be tested in the laboratory. Following Buckley et al. (2020) the cost of lime, including the cost of application to the field, is assumed to be €25 per tonne. As against Lanigan et al., (2018) and Buckley et al., (2020) which assumed a dynamic abatement of gaseous emissions and cost of abatement, this research assumes a one-off implementation of abatement measures thus the cost of liming and sampling were discounted at a rate of 20% for 5 years. The number of years used in discounting the amount of liming was based on Teagasc (2021) advice on liming which stated that a replacement of lime is required approximately every 5 years	Teagasc (2019) Teagasc (2020) Buckley et al. (2020) Teagasc (2021) Ogunpaimo et al. (2022)

*****Amended from Ogunpaimo et al., (2022)

Table 2: Assumptions Applied to Modelling Mitigation

Abatement Measure	Intervention	Abatement Potential Assumptions	Cost Assumptions	References
CLOVER	The importance of using clover as an abatement practice can be attributed to its natural fixation of nitrogen, which reduces the need for chemical fertilization, thus reducing emissions from chemical fertilizer application. The study assumes that all grassland area is reseeded with clover over a 10-year time horizon. The study also assumes that 10% of the land area is over sown with clover annually.	The nitrogen fixation of clover was fixed to a maximum of 80 kg N ha^{-1} yr^{-1}. All chemical N savings are captured through reduced protected urea fertiliser applications.	€121/ha was assumed as the contractor's rate for a full reseed of grassland with clover (FCI, 2020). €22/ha was assumed as the contractor rates for over sowing with clover (FCI, 2020). The cost of clover seed is €50 per hectare.	FCI, 2020). Buckley et al. (2020) Buckley et al. (2020) Teagasc (2017b)
		MANURE MANAGEMENT/BOVINE MEASURES		
LESS	The splashplate method which is the most popular method broadcasts the slurry over a wide area. Alternative application methods exist under the broad label of Low Emission Slurry Spreading techniques (LESS). LESS consists of the use of slurry injection, trailing hose and trailing shoe, which reduces ammonia emissions compared to the splash plate method. LESS is based on the principle of reducing the area of the ammonia emitting surface, in this case of soil/plant surface that is covered by the applied liquid manure and can reduce ammonia emissions by more than 60% when compared to emissions associated with the use of the splash plate method.	The new scenario was developed based on the assumption that 100% of slurry applied by splashplate in the base year was substituted to LESS, which a 50/50 split between trailing shoe and trial hose methods. The use of trailing hose and trailing shoe results in a 30% and 60% reduction of NH_3 emissions as against splash plate (Bittman et al., 2014; Buckley et al., 2020). Increased nitrogen recovery associated with LESS is assumed to realised through a reduction in chemical N fertiliser. It is assumed that this reduction is realised in the form of reduced protected urea use that is costed at market rates. Reductions in N_2O from storage and landspreading were almost exclusively from reduced indirect N_2O emissions associated with reduced ammonia emissions (Lanigan et al., 2018).	Costs were estimated based on relative contractor rates for application which suggests that using a 11500-litre tanker, the cost of slurry spreading by splash plate and LESS method is €65/hour and €85/hour respectively The volume of slurry spread by LESS and splash plate per hour for an 11,500- litre tanker is assumed to be $28.4m^3$ and 34 m^3 respectively.	Buckley et al. (2020) Lanigan et al. (2018) Bittman et al. (2014) Ogunpaimo et al. (2022)

***Amended from Ogunpaimo et al., (2022)**

Table 2: Assumptions Applied to Modelling Mitigation

Abatement Measure	Intervention	Abatement potential Assumptions	Cost Assumptions	References
Slurry Amendments	The emissions of CH_4 and N_2O during the slurry storage stage can be offset by the inclusion of chemical amendments (Kavanagh et al., 2019). These amendments may include such chemical as alum, ferric acid, sulphuric acid and acidic acids	The compound alum is the amendment added to the bovine slurry and that this reduces CH_4 at the slurry storage stage by 80%. The adoption rate is assumed to be 100% The adoption of the slurry amendment leads to a reduced requirement for chemical fertilizer due to the increased quantity of nitrogen captured in the slurry and later returned to the soil at the land spreading stage of the manure management chain.	The treatment cost per volume of slurry treated is assumed to be €2.34 per m^3 and €4.40 per m^3 for dairy and cattle slurry respectively (Kavanagh et al., 2019) . The extra N retained over the baseline level represents a benefit and is accounted for as the cost saving of protected urea fertiliser	Kavanagh et al. (2019) Buckley et al. (2020) Lanigan et al. (2018) Lanigan et al. (2018) Teagasc (2017b) Ogunpaimo et al. (2022)
Covering of Slurry Stores	NH_3 reduction at the slurry storage stage leads to higher nitrogen retention for use within the farm system. This in turn reduces the requirement for chemical nitrogen fertiliser for a given level of agricultural production. All cover types were posited to reduce NH_3 emissions (Kupper et al., 2020)	The assumptions behind the adoption of the covering of slurry stores are based on the use of a flexible floating cover and an implementation rate of 100% (that is, it involves moving all uncovered stores to covered stores). The emissions factors for covered stores is 50% lower than for uncovered slurry stores. (Misselbrook et al., 2016.) Reductions in N_2O from storage and landspreading were almost exclusively from reduced indirect N_2O emissions associated with reduced ammonia emissions (Lanigan et al., 2018) Reduction in chemical N fertiliser is assumed to be realised in the form of reduced protected urea use that is costed at market rates per tonne of protected urea (Wall, 2020a).	On the cost side, the assumption was based on the report of Reis et al. (2015) which assumes a cost of €1.5 per m^3 of slurry to replace an open slurry store with a covered slurry type. The total cost of replacing an open slurry to a covered type was discounted over a period of 10 years	Buckley et al. (2020) Reis et al. (2015) Misselbrook et al. (2016.) (Ogunpaimo et al., 2022)
Crude Protein	Excess crude protein (over requirement) in the diet of livestock's leads to higher N excreation rates and ultimately higher ammonia emissions (Sajeev et al., 2018a; Buckley et al., 2020) This abatement measure works by influencing the amount of nitrogen excreted by livestock and by extension the amount entering the manure management chain (Buckley et al., 2020).	It is assumed that the average dairy cow was fed 1,045 kg of concentrates (Buckley et al., 2020). Furthermore, it is assumed that a 1% decrease in the crude protein composition of dairy concentrates leads to a decrease of 1.5 kg in the N excretion rate of dairy. The N excretion rate for the non-dairy animals considered in this study was reduced by a percentage reduction obtained by the ratio of the new dairy N excretion rate to the old dairy N excretion rate. GHG abatement is accounted as reductions in N_2O emissions associated atmospheric decomposition, leaching and indirectly from reduced ammonia emissions (Lanigan et al., 2018).	A 1 percentage point crude protein reduction results in a €6 per tonne reduction in the price of dairy concentrates, based on the market price differential between the two protein ingredients in 2020 (Buckley et al., 2020).	Shalloo et al. (2018); (O'Brien et al., 2018) O'Brien and Shalloo (2019).

***Amended from Ogunpaimo et al., (2022)**

4.0 Results

This section presents results around the GHG abatement potential, cost, cost-effectiveness and MACC analysis for the different mitigation measures examined.

4.1 Baseline scenario of farm-level GHG emissions

Given that some farms may already adopt the abatement measures in the baseline scenario, Table 3 gives a description of the baseline scenario of total farm level GHG emissions across the 5 farm system types in addition to the current adoption rate of mitigation measures. The baseline year of analysis is 2020.

Table 3. Baseline Emissions and Percentage adoption of abatement measures by farm type

	Specialist Dairy	Cattle	Specialist sheep	Specialist Tillage	Mixed Livestock	All farms
	(N=16,146, 60.8 ha^{-1})	(N=54,020, 33.9 ha^{-1})	(N=143,22, 44.3 ha^{-1})	(N=6,879, 61.2 ha^{-1})	(N=1,877, 64.4 ha^{-1})	(N=92,264, 42.6 ha^{-1})
Baseline Emissions (tCO_2e) per farm	518	132	127	139	331	199
Baseline Adoption of Abatement Measures						
1. % of fertiliser applied as Protected Urea	16 %	3%	8%	2%	3%	6%
2. % of soils at optimum pH	54%	50%	50%	78%	66%	53%
3. Grass clover swards	0%[a]	0%[a]	0%[a]	0%[a]	0%[a]	0%[a]
4. % of slurry applied by Low emissions slurry spreading (LESS) equipment	50%	15%	9%	17%	25%	20%
5. Use of Slurry amendments	0%[a]	0%[a]	0%[a]	0%[a]	0%[a]	0%[a]
6. % of farmers at optimum level of crude protein in dairy cow diet	0%[a]	0%[a]	0%[a]	0%[a]	0%[a]	0%[a]
7. % of slurry stores that are covered	85%	93%	95%	91%	98%	92%

Source: Authors Computation of 2020 NFS and assumptions data. [a] Own assumption

4.2 Farm-level GHG Abatement Potentials

Firstly, the result of the GHG abatement potentials showed that the fertilizer options reduce higher levels of GHG emission across the five farm categories studied in this report (Table 4). The clover has the highest abatement potential of about 12 tCO_2e for the all farm, followed by the slurry amendments (11 tCO_2e), then protected urea (8 tCO_2e). The abatement potential recorded by clover is about 12 times that of the

LESS measure (1 tCO_2e). For the all farm, clover and slurry amendments account for about 65% of the total abatement potential.

Disaggregating the result into farm system typologies, the use of clover also has the highest abatement potential among the farm systems except for the dairy farm and the tillage farm. The abatement potential of clover for the mixed farm is highest (20 tCO_2e) and it is about two times that of the cattle farm.

The bovine measure (LESS, slurry amendments, reduction in crude protein and covering of slurry stores) indirectly reduces the N_2O emissions through a direct reduction of NH_3 emissions at the manure management stage (Eory et al., 2021). Slurry amendments not only abate the indirect emissions of N_2O but also the direct emissions of CH_4 (Lanigan et al., 2018). In our study, the slurry amendment measure has the highest GHG reduction potential for dairy (28 t CO_2e) and the second-highest GHG abatement potential for the other farm typologies after clover. The proportion of abatement potential of both clover and slurry amendments across the different farm types ranges from as low as 33% for the specialist tillage farm to 72% for the specialist sheep farms.

The use of protected urea is also important in reducing GHG emissions among all farm categories. The fertilizer measures result in higher abatement measures on grass-based farms (dairy, tillage and mixed livestock) compared to sheep and cattle farms. The average abatement potential of the protected urea measure ranges from 4 t CO_2e for the sheep farm to 18 t CO_2e for the tillage farm. When the typology of the farm is not considered an average Irish farm will abate 8 t CO_2e (Table 4) while replacing protected urea for straight urea and CAN fertilizer.

The LESS measures despite reducing GHG emissions across all farm categories; rank differently in the abatement of GHG emissions. The LESS strategy has a 0.82 t CO_2e level of abatement for a typical Irish farm, the option is more efficient in abating GHG emissions for the mixed livestock farm (1.8 t CO_2e) compared to other farm categories.

While the analysis of abatement potentials indicates the volume of abatement for individual measures, in reality, the implementation of abatement measures is usually carried out in combination with other measures. Therefore, it is imperative to also study the conflicting or complementary relationships that may exist between and amongst these measures.

The combined GHG abatement potentials are also shown in Table 4, the combined GHG abatement potentials involve the interaction of the individual measures abatement potentials but not their summation. In general, the level of abatement across the farm types and the different measures is more than the abatement potentials of individual measures but less than the total abatement potentials, this signifies the existence of interaction effects amongst the measures. When all abatement measures have interacted, the abatement potential for all measures is about 28 tCO_2e when farm heterogeneities are not taken into consideration. Otherwise, the abatement potential of all measures ranges from as low as 12 tCO_2e for the specialist farm to 78 tCO_2e for the specialist dairy farm.

Table 4 Farm-level GHG Abatement Potentials

Abatement potential (tonnes CO2 equivalent) per farm	**Specialist Dairy**	**Cattle**	**Specialist sheep**	**Specialist Tillage**	**Mixed Livestock**	**All farms**
1. Protected Urea	21	4	4	18	11	8
2. Liming	8	2	1	4	5	3
3. Clover	26	10	9	5	20	12
4. Low emissions slurry spreading (LESS)	2	1	0	0	2	1
5. Slurry amendments	28	8	6	6	18	11
6. Reduction in crude protein	1	0	0	0	1	0
7. Covering of slurry stores	0	0	0	0	0	0
Total	86	25	20	33	57	35
* Combined Measure – when accounting for interactions	78	17	12	32	46	28

4.3 Cost of Farm-level Abatement

It is important to assess the cost of abatement before estimating the cost-effectiveness of the measure. Financial benefits of implementing an abatement measure could be accrued as a need for reduced chemical nitrogen. It is indicated in Table 5 in the appendix that reduction in crude protein and fertilizer measures accrues benefit to the farmer in their implementation.

4.4 Marginal Abatement Cost Curve

A negative sign (-) implies a win-win scenario for the farmer, that is, the mitigation option reduces GHG emissions and saves costs for the farmers, while a positive sign (+) implies that a win-lose scenario where an option despite reducing GHG emissions but has some costs attached to its implementation.

The cost-effectiveness of the GHG reduction for the abatement measures is presented in Table 3 and further illustrated by figures 3a-3f. The GHG cost-effectiveness is measured in euros per tonne of carbon dioxide equivalence (€ $t^{-1}CO_2e$). The price of carbon was set at €33.50 $t^{-1}CO_2e$ following the information provided by the Ireland Revenue Services (IRS., 2022), it is necessary to know the cost of carbon because it is not advisable to adopt those measures that are more expensive than carbon, that is, cost-prohibited measures. The cost-effectiveness (MAC) for all farms ranges from -€386.01 $t^{-1}CO_2e$ to €81.16$t^{-1}CO_2e$ with the reduction in crude protein as the most cost-effective measure (-€386.01 $t^{-1}CO_2e$), followed by the liming measure (-€134.86 $t^{-1}CO_2e$) and protected urea (-€14.88 $t^{-1}CO_2e$). All fertiliser measures (that is, liming, clover and protected urea) are cost-beneficial for the GHG MACC, whereas all of the bovine measures (except the reduction in crude protein) are cost-positive.

Table 6 GHG Farm-level Cost-effectiveness across Different Farm Typologies

Cost-effectiveness GHG (€ per tonnes abated)	Dairy	Cattle	Sheep	Tillage	Mixed	All
1. Protected Urea	-€17.17	-€12.90	-€20.67	-€13.24	-€15.00	-€14.88
2. Liming	-€199.60	-€119.19	-€139.60	-€120.36	-€77.19	-€134.86
3. Clover	-€77.23	-€9.07	€161.86	€61.08	€4.61	€11.73
4. Low emissions slurry spreading (LESS)	€0.31	€0.80	€0.55	€0.16	€1.00	€0.64
5. Slurry amendments	€51.64	€98.12	€64.14	€39.58	€115.22	€81.16
6. Reduction in crude protein	-€750.12	-€331.91	-€298.04	-€172.92	-€447.06	-€386.01
7. Covering of slurry stores	€62.01	€48.23	€32.48	€13.11	€4.12	€44.56
*Combined Measure – when accounting for interactions	-€53.43	€72.47	€78.09	-€37.39	€72.93	€44.42

Source: Authors' Computation of 2020 NFS and NIR data

The cost-effectiveness ranking of mitigation measures for the average dairy farm follows closely that of all farm categories with the reduction in crude protein measure being the most cost-beneficial measure. In contrast to all farm categories, the clover measure is cost-beneficial and ranked third in the dairy farm (-€77.23 $t^{-1}CO_2e$). Similarly, slurry amendments and the covered stores are cost-prohibited for dairy farm MACC as it is for all other farm systems (Figure 3b-f)

The cost-effectiveness ranking for a cattle farm differs from the all farm when it comes to the ranking of clover and LESS measures, where they are ranked 4th and 5th position respectively unlike the all farm category. The cost-effectiveness ranking for the sheep and tillage farm differs from the other farm types. The clover is a cost-prohibited measure in contradiction to the measure's position for other farm categories earlier outlined. The justification of this is that, unlike the other farm categories, the cost of the nitrogen saved from reduced fertiliser application is not enough to offset the cost of clover reseeding. On both farms, the covered stores are also ranked as a cost-neutral measure (Figures 3d and 3e) measure as against the cost-effectiveness ranking for the dairy and cattle farms.

The result of the CE in Table 3 showed that the combination of abatement measures in reducing GHG emissions doesn't necessarily lead to a lower cost implication. Combining all the abatement measures leads to a cost-beneficial scenario for only the dairy and tillage farms.

5. Discussions

This paper investigates the effects of abatement measures on GHG emissions taking account of farm system heterogeneity and efficient policy design. While the measures selected in this study have proven to work well for NH_3 reduction (Lanigan et al., 2015; Buckley et al., 2020; Ogunpaimo et al., 2022) it is imperative to know the behaviour of these measures in reducing GHG emissions, the effect of the interactions of these measures on GHG emissions and address farm-system heterogeneity to ensure optimal GHG reduction across the different farm systems.

This study finds that reducing crude protein in diets is the most cost-beneficial option for reducing GHG emissions. This argument is supported by Sajeev et al. (2018b); Sajeev et al. (2018a) and Huhtanen and Huuskonen (2020) which reported that the reduction of crude protein in diets is the most appropriate measure for reducing N_2O emissions. The reduction of crude protein in diets reduces GHG emissions by reducing indirect N_2O emissions from manure management (Chojnacka et al., 2021), direct emissions of N_2O from managed soils through the reduced use of organic fertilizer, the reduced urine and animal dung at grazing (Abbasi et al., 2018) and also reduces indirectly by reducing the N_2O losses through leaching and atmospheric deposition. Kidane et al. (2018) also reported that the reduction of crude protein in diets doesn’t reduce CH_4 emissions but reduces urine nitrogen.

While the crude protein in diets is the most cost-effective measure in this study, the abatement potential of using this measure is highest on dairy and mixed livestock but almost negligible for the cattle, sheep and tillage farms. The difference in the results across the farms' system could be attributed to the presence of heterogeneity on foot of higher concentrating feeding associated with dairy production.

This report buttress that of other research on the importance of substitution of CAN fertiliser for protected urea fertiliser in reducing GHG emissions. Previous work (e.g. Martins et al., (2017) and Tzemi and Breen (2019)) affirmed that the use of protected urea in form of urease inhibitors added to urea will abate NH_3 emissions and by extension N_2O emissions in comparison with other traditional fertilisers. Our findings affirm the use of protected urea in reducing GHG emissions in line with the literature (Krol et al. (2020). Given the higher emission factor of protected urea than straight urea for GHG reduction, the existence of a potential antagonistic (between the reduction of GHG and NH_3 emissions) effect of replacing straight urea for protected urea is possible. However, other studies such as Wang et al. (2020) exhibited a certain level of uncertainty surrounding the use of protected urea in reducing N_2O emissions.

In Lanigan et al., (2018), the use of protected urea was ranked as a cost-effective (win-lose) measure as against our study where it is mainly a cost-beneficial measure (win-win) measure, the difference in our results is attributable to the baseline assumptions in addition, this study also used a more recent activity data and data on emission factors compared to Lanigan et al., (2018). Unlike Lanigan et al., (2018) where only 50% of CAN fertiliser is replaced by protected urea, our findings showed that a replacement of both all CAN fertilisers yields a better result for the use of protected urea.

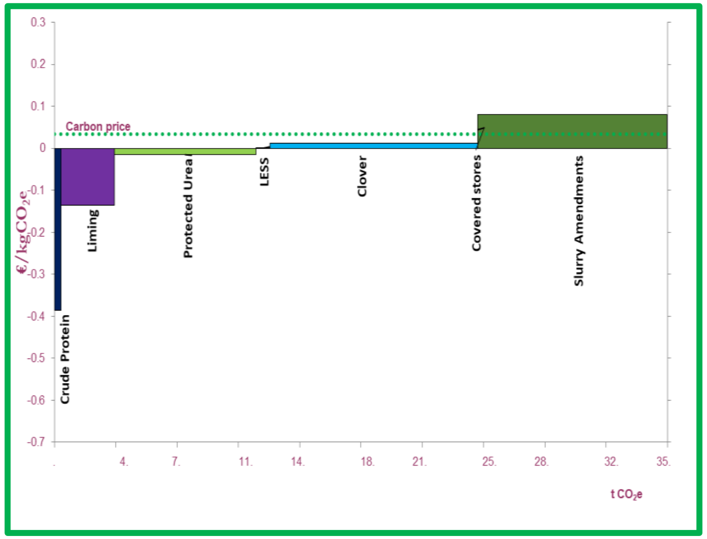

Fig. 3a. All farm

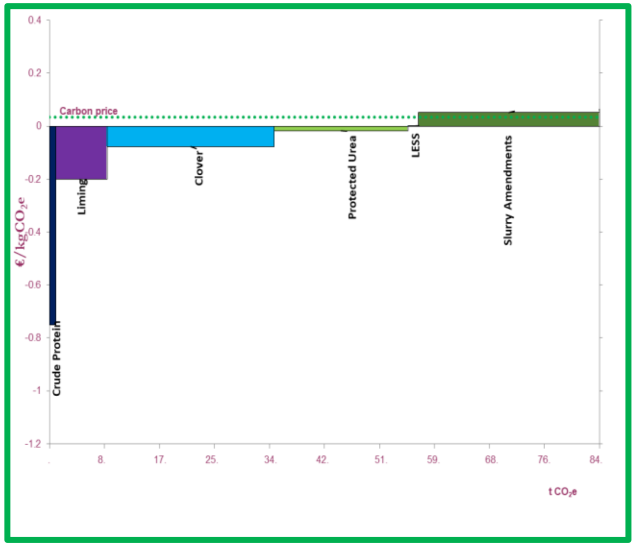

Fig. 3b. Dairy farm

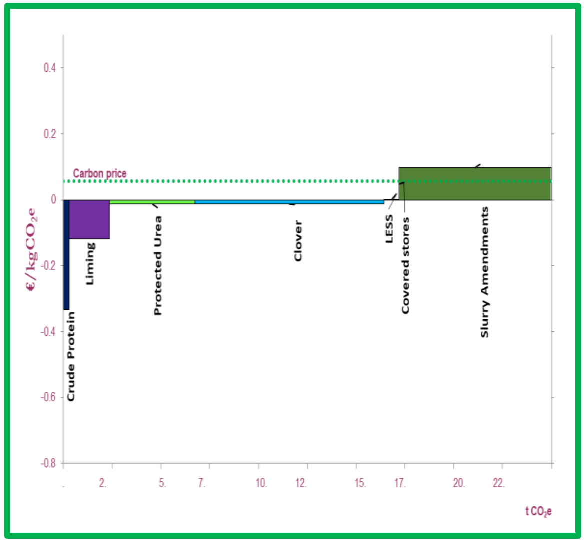

Fig. 3c.Cattle farm

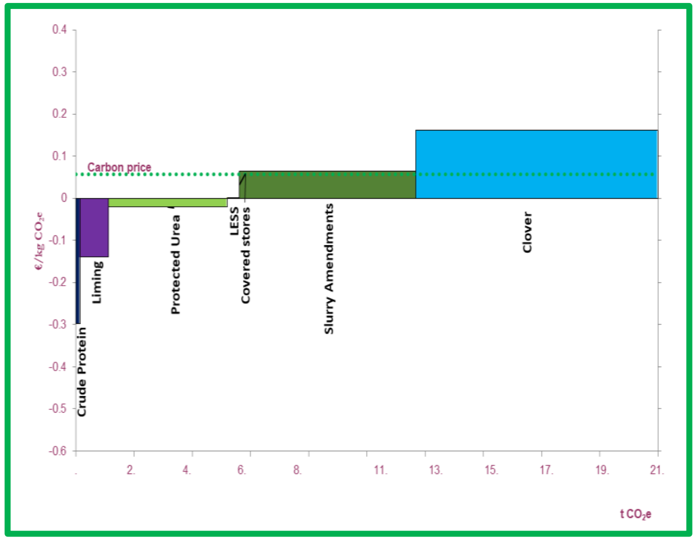

Fig.3d. Sheep farm

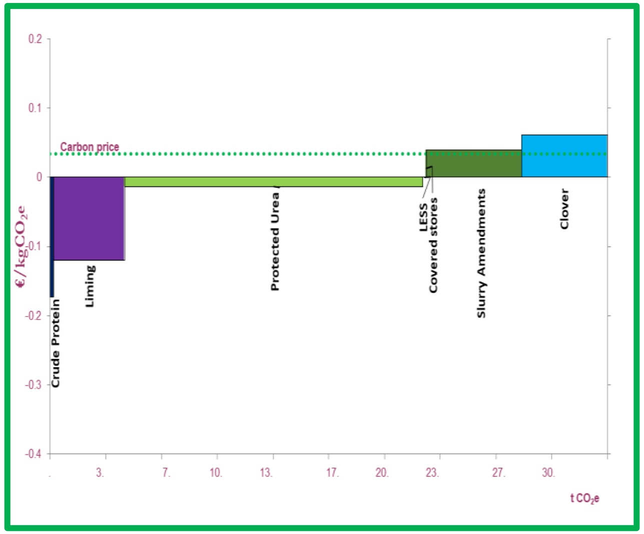

Fig. 3e. Tillage farm

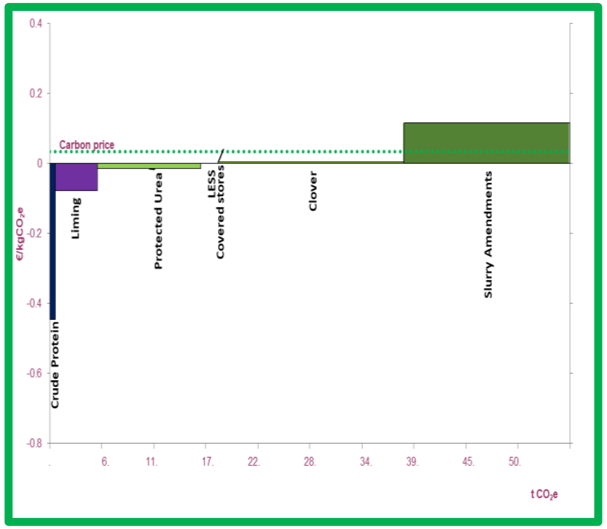

Fig. 3f. Mixed livestock farm

Figure 3: Diagram showing the MACC Curves for Different Farm Systems

Due to the presence of heterogeneity, variations exist in the abatement potentials across the different farm systems. The impact of protected urea in reducing GHG emissions was indicated more on the dairy, tillage and mixed livestock farms compared to the other farm systems. Similarly, the ranking of protected urea changes across the different MACC diagrams which typically supports the presence of farm-system heterogeneity. As a farmer or policy maker, it it important to put farm heterogeneity into consideration as it ensures the optimal level of emission reduction.

The use of clover as a GHG abatement strategy lowers N_2O emissions by reducing the need for inorganic fertilisers and urea application (Yan et al., 2013; Herron et al., 2021; Schils et al., 2005). While it is understandable that white clover reduces GHG emissions, contradictory information exists on which of the GHG gases white clover reduces. The result of Yan et al. (2013) with a focus on pasture-based milk-producing systems shared similar findings with this study that the use of white clover leads to a significant reduction in N_2O emissions and no change in CH_4 emissions, on the other hand, Hammond et al. (2011) revealed that the use of white clover reduces CH_4 emissions from sheep in New Zealand.

Contradictory evidence exists on the application of lime to reduce soil acidity and its effect on GHG emissions, while some literature agrees that liming reduces GHG emissions (Hénault et al., 2019; García-Marco et al., 2016; Lanigan et al., 2018), others avail that it poses a threat by increasing GHG emissions (Shoghi Kalkhoran et al., 2019). This contravening evidence may be a result that the application of lime has some benefit in reducing GHG emissions by lowering both direct and indirect N_2O emissions but increases GHG emissions through CO_2 emissions associated with carbon mineralization (Goulding, 2016; Kunhikrishnan et al., 2016; Wang et al., 2021; Lanigan et al., 2018).

Contradictory evidence exists on the application of lime to reduce soil acidity and its effect on GHG emissions, while some literature agrees that liming reduces GHG emissions (Hénault et al., 2019; García-Marco et al., 2016; Lanigan et al., 2018), others avail that it poses a threat by increasing GHG emissions (Shoghi Kalkhoran et al., 2019). This contradictory evidence may be a result that the application of lime has some benefit in reducing GHG emissions by lowering both direct and indirect N_2O emissions but increases GHG emissions through CO_2 emissions associated with carbon mineralization (Goulding, 2016; Kunhikrishnan et al., 2016; Wang et al., 2021; Lanigan et al., 2018).

Thus, a balance between the reduction in N_2O emissions and CO_2 emissions on the farm will determine whether it leads to the abatement of GHG emissions. In the case of this study, the reduction of N_2O emissions far outweighs that of the CO_2 emissions across the different farm systems. In addition, the adoption of this strategy will lead to a win-win situation where it not only reduces the overall GHG emissions but also saves the farmer some money, therefore we agree that it is an important strategy in the abatement of GHG emissions (Eory et al., 2021).

Similar to the heterogeneity issue addressed in this study, the contradictory result revealed by the different studies (aforementioned) may be due to the presence of heterogeneity (farm system, location) or other reasons such as differences in underlying assumptions. In this study farm, system heterogeneity for the clover measure is more evident in the ranking of the measure, the clover measure fluctuated from being a cost-beneficial measure (Lanigan et al 2018; Eory et al., 2021) to being a cost-prohibited measure depending on the farm system. Similar to the protected urea measure, the difference in the abatement potentials of clover of this study in relation to Lanigan et al., (2018) is attributed to the difference in the underlying baseline assumption that all grassland areas are reseeded with clover farms as against a 15% to 25% grassland area.

The LESS measure reduces GHG emissions by lowering the N_2O emissions from atmospheric depositions and runoff. The result obtained from this study showed that although LESS measure reduces GHG emissions across most farm systems. However, the impact of LESS in reducing GHG emissions is not as profound as that of NH_3 emissions (Ogunpaimo et al., 2022). The finding of this study on LESS supports the result of Wagner et al. (2015) Lanigan et al., (2018), and Eory et al., (2021) but contradicts some studies (Meade et al., 2011; Bourdin et al., 2014). The latter studies argued that the implementation of LESS measures leads to increased N_2O emissions. More importantly, the measure is ranked as a cost-effective measure in reducing GHG emissions. The findings of this study also contradict the result of Wagner et al. (2015), that reported that the use of covered stores led to increasing in N_2O emissions, the difference in the result may be attributed to the type of manure storage techniques used in the study.

Slurry amendments are an important strategy for reducing GHG emissions (Kavanagh et al., 2019). In this study, the use of slurry amendments indicated the highest level of GHG amongst the manure management options (that is LESS, covered stores and slurry amendments) and records the highest abatement potential for the dairy farm system. The use of slurry amendments reduces GHG emissions by reducing CH_4 emissions and indirect emissions of N_2O. This result follows closely the report of Lanigan et al., (2018) on the ranking of the abatement measure, however, in our study, slurry amendments is cost prohibited as opposed to Kavanagh et al. (2019). A difference in the baseline assumption and the type of slurry amendments used, carbon price and scale of analysis could be responsible for the divergent results obtained from the studies.

It is evident that across the different farm system types that there exist variations in the mitigation measures' abatement potential, abatement cost and cost effectiveness. This reflects the presence of farm heterogeneity across the different farm systems. While the literature on GHG MACC is vast, those investigating the presence of heterogeneity on farms are very limited, especially in the Republic of Ireland. One such study is that conducted by Jones et al. (2015) on sheep farms, the study buttressed the importance of assessing the presence of heterogeneity across farms. In this study the ranking of clover varies between a cost-beneficial to a cost-effective measure, these variations are mainly due to biophysical conditions of the different farm types. Similarly, Krimly et al. (2016) support our finding on the issue of farm heterogeneity and its influence on the different farm types, this research argued that different farm biophysical conditions affect the optimality of GHG emission reduction. Tang et al., (2021) also highlighted the importance of considering farm heterogeneity when assessing and recommending GHG measures. De Cara and Jayet (2000) pointed out that the behaviours of farms to the GHG abatement measures differ, in their study, while the arable farms are well positioned due to reduced abatement cost as against the livestock farmers. In Ireland, although the study worked on NH_3 abatement Ogunpaimo et al. (2022) argued in favour of assessing farm heterogeneity, the study concluded that the absence of farm-heterogeneity in MACC construction could lead to sub-optimal levels of emission reductions

In the case of combining measures to account for interactions, various studies (Kesicki & Ekins, 2012; Eory et al., 2018a; Kesicki & Strachan, 2011; Fellmann et al., 2021) has shown the importance of interactions in MACC studies which may be evident in form of complementary and conflicting measures in reducing GHG emissions. The combined measures have a higher abatement potential than the individual measures across the different farm systems, however, on the MAC side, the combined measures are only cost-beneficial for two farm systems. The implication of this is that a blanket policy recommendation that points to combining mitigation measures may lead to sub-optimal outcomes. It is also noteworthy that while some measures are mostly cost-prohibited when assessed individually, they behave better when combined with other measures for certain farm systems (Fellman, 2021). For instance, while the use of slurry amendments is mostly cost-prohibited across the different farm systems, the combined measure for the dairy and tillage farms is cost-beneficial; this may be due to the impact of the other cost-beneficial measures limiting the influence of slurry amendments. Just like in Webb Webb et al. (2006) the interactions of measures are not additive.

It is noteworthy that certain limitations are inherent in this study. One of which is that regional heterogeneity was not considered. Different biophysical conditions of farms may influence the measures that effectively minimize the GHG emissions in the area. In addition, the total GHG abatement potential realisable across the different locations may vary (Cui et al., 2022). It is also noteworthy that other abatement measures that have proved to reduce GHG emissions such as the improved beef maternal traits were not considered in this study mainly because of the difficulty of assessing the excluded measures at the farm level as such measures are assessed on a national scale. Thus the total GHG abatement potential across the farm systems, in reality, will be above those recorded in this study.

6. Conclusions

This study confirmed that the suite of mitigation measures assessed in this study are effective in reducing GHG emissions at the farm level. ranged from cost-beneficial to cost-prohibited measures with cost-effectiveness. The study revealed the presence of interrelationship amongst the mitigation measures in reducing GHG emissions, however, the combination of mitigation measures in form of interactions does not necessarily lead to a cost-effective solution since different farms behaved differently.

In furtherance to the limited literature on GHG farm system heterogeneity, this study investigated the importance of accounting for farm heterogeneity in constructing GHG MACC curves and revealed that one MACC type does not represent the prevailing situation across different farm systems. Thus, this study recommends that farm heterogeneity in form of systems, location and soils should be put into consideration when formulating policy underpinning GHG emission reduction. The study recommends that an integrated assessment that would look into overall cost saved when these measures are implemented to reduce multi-pollutant as against a single-pollutant assessment advised.

It is noteworthy that an increase in carbon price without a decrease in the cost of fertilizer could see most of the measures including slurry amendments become cost-effective. While studies have shown that the measures considered in these studies could well abate both NH_3 and GHG emissions, further studies investigating their impact on water pollution and biodiversity losses should also be considered.

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