Mitigation of gaseous emissions from dairy livestock: A farm-level method to examine the financial implications

M. Cantillon[a,b*], T. Hennessy[b], B. Amon[c,d], F. Dragoni[c], D. O'Brien[a]

[a] *Teagasc, Crops, Environment and Land Use Research Centre, Johnstown Castle, Co. Wexford, Ireland*

[b] *Cork University Business School, University College Cork, College Road, Ireland*

[c] *Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany*

[d] *University of Zielona Gora, Faculty of Civil Engineering, Architecture and Environmental Engineering, Poland*

[*] Corresponding author: marion.cantillon@teagasc.ie

Tel.: +353 53 917 1221

Abstract

Feeding the world's population while minimising the contribution of agriculture to climate change is one of the greatest challenges facing modern society. This challenge is particularly pronounced for dairy production where the carbon footprint of products and the mitigation costs are high, relative to other food stuffs. This paper reviews a number of mitigation measures that may be adopted by dairy farmers to reduce greenhouse gas emissions from their farms. A simulation model is developed to assess the cost-benefit of a range of mitigation measures. The model is applied to data from Ireland, a country with a large export-oriented dairy industry, for a range of farms including top, middle and bottom performing farms from a profitability perspective. The mitigation measures modelled included animal productivity, grass production and utilisation, better reproductive performance, early compact calving, reduced crude protein, decreased fertiliser N, protected urea, white clover, slurry tank cover and low emission slurry spreading (LESS). The results show that over half of the greenhouse gas abatement potential and most of the ammonia abatement potential were realised with cost-beneficial measures. Animal and feed-related measures that increased efficiency drove the abatement of GHG emissions. Low-emission slurry spreading was beneficial for the bottom and middle one-third of farms, while protected urea and reducing nitrogen use accounted for most of the ammonia abatement potential for the most profitable farms. Results showed that combining mitigation measures resulted in a decrease of 23%, 19%, and 12% in GHG emissions below 2020 levels for the bottom, middle, and top performing dairy farms, respectively. The findings imply that top dairy farms, that are already managed efficiently and optimally, may struggle to achieve the national and international GHG reduction targets with existing technologies and practices.

Keywords: Farm-specific, Marginal Abatement Cost Curve, Greenhouse gas, Ammonia, Climate change, Financial Impact

Introduction

Livestock are culturally and economically important to rural communities throughout the world. They not only yield a variety of valuable food products but also form the backbone of livelihoods for countless farmers. In Ireland, dairy farming holds a central position in rural life. The dairy industry is deeply woven into the cultural and economic fabric of the country. It supports thousands of farming families, providing them with a sustainable source of income. Additionally, dairy farming traditions are passed down through generations, reinforcing the cultural significance of this industry. Livestock contributes significantly to biodiversity and habitat conservation. Grazing animals, including those in Ireland, play a crucial role in managing grasslands, supporting biodiversity, and ensuring the growth of native plants. Additionally, the diversity of livestock breeds raised on these farms helps safeguard genetic diversity, ensuring the resilience of livestock and local ecosystems. Mitigating gaseous emissions from livestock systems is a critical imperative in contemporary agriculture. The dairy sector, in particular, plays a pivotal role in this effort, given its substantial environmental footprint. Dairy farms, often family-owned, are at the forefront of initiatives aimed at reducing emissions and implementing sustainable practices. These efforts are integral in curbing the environmental impact and safeguarding the long-term viability of dairy farming. Traditional methods in the industry, especially those about manure management and feed efficiency, are being re-evaluated and refined to address emissions concerns while ensuring continued productivity. To sustain profitability in farming while feeding a growing population, a delicate balance is needed between sustainable

62 practices and managing greenhouse gas (GHG) emissions. Various mitigation strategies have
63 been researched, ranging from land management and animal practices. Each strategy has
64 different abatement impacts and investments.

65 In the EU-28, the value of animal output and livestock products was € 170 billion, or 40%
66 of all agricultural activity. Additionally, almost 4 million people are employed on livestock
67 farms throughout Europe (Peyraud & MacLeod, 2020). Growth in livestock production has
68 multiple benefits for the economy, human health, and nutrition. However, it has the
69 potential to harm one or more aspects of the environment. Livestock production releases
70 nutrients into ecosystems, which cause water pollution, soil contamination, or biodiversity
71 loss (FAO, 2009; Burchill et al., 2016). Livestock also generates gaseous pollutants, namely
72 GHG and ammonia (NH_3) emissions that adversely impact nearby ecosystems. Greenhouse
73 gas emissions are the primary driver of global warming and climate change, and NH_3 is a key
74 air pollutant (IPCC, 2013; EMEP, 2019). The Paris Agreement of the United Nations (UN) on
75 reducing GHG emissions and the UN Convention on Long-Range Transboundary Air Pollution
76 (CLRTAP) puts ceilings on NH3. The goal of the Paris Agreement is to restrict the global
77 temperature increase to below 2°C this century, which translates into a 43% GHG emissions
78 reduction by 2030 and net-zero levels by 2050 (UNFCCC, 2023; UN, 2023). The purpose of
79 the CLRTAP is to avoid the exceedance of critical loads of NH_3 in sensitive ecosystems.
80 Sensitive ecosystems might include old forests, terrestrial herbaceous areas, coastal dunes,
81 and wetlands.

82 Most of the world's NH3 losses emanate from livestock farming and fertiliser N use (Ma
83 et al., 2021; Beaudor et al., 2023). According to Beaudor et al. (2023) 78 per cent of it is
84 attributed to soil volatilisation, which is fuelled by the application of fertiliser and manure,

85 while the remaining per cent is attributable to interior emissions from animal housing,
86 yarding, and storage. These sources are also the principal drivers of agricultural GHG
87 emissions, constituting about 12% of global emissions (OECD/FAO, 2021). Decreasing
88 gaseous emissions from livestock production is challenging, but it can be achieved by
89 improving farming practices and agricultural technologies. Many farm practices and
90 technologies already exist to mitigate GHG and NH_3 emissions, e.g., restoration and
91 conservation of the soil fertility and water, incorporating legumes into swards, spreading of
92 nitrification inhibitors, extended grazing, genetic and genomic selection of animals (Gerber
93 et al., 2013; Pellerin et al., 2017). The adoption of these mitigation measures by farmers
94 depends on several factors, including ease of use, agricultural education, social
95 acceptability, efficiency, and costs. The cost factor is among the most important for
96 adoption and is generally assessed with a marginal abatement cost curve (MACC). This
97 methodology estimates the abatement potential of a suite of mitigation practices and
98 technologies relative to a baseline scenario. It ranks them according to their financial cost
99 (Lanigan & Donnellan, 2019). The approach aims to identify the most cost-effective options
100 to meet emission reduction targets.

101 Marginal abatement cost curves are derived using either a top-down or bottom-up
102 approach. A top-down MACC normally employs a general equilibrium model to determine
103 the cost of emission reductions for the overall economy (MacLeod et al., 2010). Conversely,
104 a bottom-up or engineering MACC brings together data on individual measures' costs and
105 mitigation potential and calculates their average cost-effectiveness (Eory et al., 2018).
106 Generally, engineering MACCs are used to determine the mitigation potential of the farming
107 sector at a country level (Eory et al., 2018). Projected growth rates and expert judgment
108 about costs and uptake of mitigation measures strongly influence the outputs of this

approach. To try and overcome this issue, a limited number of MACCs have been applied to examine farms representative of a region or country (Jones et al., 2015). This analysis is helpful for visualising mitigation costs at a farm level and provides general advice on reducing emissions. This analysis is helpful for visualising mitigation costs at a farm level and for providing general advice on reducing emissions. This may also support policy makers in establishing emission strategies. However, mitigation costs are specific to each livestock farm and are potentially related to a farm's financial performance. Thus, to provide targeted advice to livestock producers about mitigating emissions, a MACC type approach is required that can estimate mitigation costs for farms with varying levels of profitability.

The primary purpose of this study was to develop a MACC methodology capable of determining the financial implications associated with mitigating gaseous emissions from livestock at a farm-level for a heterogeneous selection of representative farms. This methodology was postulated to capture heterogeneity in GHG and NH_3 abatement costs that need to be adequately accounted for in sectoral level or top-down approaches. The farm-level MACC was applied to case study livestock farms that represented the Irish dairy farm system's top, middle, and bottom averages. Applying this approach on these farms was expected to demonstrate that mitigation costs for top performing livestock farms are greater than the costs for farms with average or below-average performance. Net margin was the indicator used to determine the farm's performance. Enhancing our grasp of the expenses and advantages associated with mitigation efforts on individual farms can aid in crafting more impactful policies that foster behavioural shifts within the agricultural sector, carrying substantial policy implications. The agricultural carbon market mechanism is a concept that holds significant potential for incentivising sustainable practices within the agricultural sector. However, it is essential to acknowledge that such a market still needs to

be fully developed in the Irish context. While initiatives and discussions surrounding carbon credits and offsetting have gained traction internationally, their implementation in Ireland is still in its nascent stages. The specific nuances of such a mechanism in the context of Irish agriculture, including factors like farm size, diversity of agricultural practices, and regional variations, require careful consideration. There is a need for further research, policy frameworks, and stakeholder engagement to pave the way for a robust and effective agricultural carbon market in Ireland.

Materials & Methods

Farm selection

The case study farms chosen for this study were located in the Republic of Ireland. Farming in Ireland is predominately grass-based and generally relies on livestock, particularly cattle and sheep, to convert pasture into agricultural products. The majority of Irish farms, about 55%, specialised in beef production. Specialist sheep production was the next most common farming system, with 17,435 farms, followed by specialist dairy production with 15,319 farms. Currently, the Irish agricultural sector is worth about €6 billion, with exports making up the bulk (90%) of dairy and red meat sales (DAFM, 2022). Nationally, it is also a significant source of GHG (33%) and NH_3 (98%) emissions. Beef and dairy farms are the main drivers of the country's agricultural emissions. For the purpose of this study, dairy farms were chosen.

The National Farm Survey (NFS), operated by Teagasc, estimates gaseous emissions from livestock farms in Ireland annually. The NFS aims to monitor the financial performance and sustainability of the agricultural sector. Information from the NFS is shared with the Farm Accountancy Data Network (FADN) of the European Union (Dillon et al., 2021). The NFS is

156 undertaken annually on a nationally representative sample of farms. Generally, 900 to 1,000
157 farms are included in the survey. A random sampling methodology is used to select farms.
158 The NFS weights farms according to the land area using aggregation factors from the Central
159 Statistics Office (CSO, 2022) to ensure the survey is representative. Farms are assigned to
160 one of the following systems based on their dominant enterprise: Dairy, cattle rearing,
161 cattle other, mixed livestock, tillage, and sheep. The value of agricultural products in terms
162 of standard output determines the chief enterprise(s) on a farm.

163 Case study livestock farms were picked from the NFS for Ireland's most valuable
164 agricultural subsector, i.e. dairy (Bord Bia, 2022). Within the dairy category in the survey,
165 dairy farms were ranked by gross margin and case studies were chosen from the average
166 bottom, middle and top one-third of farms. Relevant practices and technologies to mitigate
167 gaseous emissions were applied on these farms. The cost of each mitigation strategy were
168 calculated and represented in the financial in the MACC. The baseline year chosen for the
169 analysis was 2020. In order to compare mitigation potential on a land use perspective,
170 results are presented on a per hectare basis. The model is structured that the results can be
171 expressed on per animal, per unit of output also.

172 *Mitigation measures*

173 Multiple mitigation measures have been researched to reduce emissions from livestock
174 farming systems (Hristov et al., 2013). The applicability of a mitigation measure to a
175 livestock system depends on various factors, including:

176 • Farm location- geographical context and proximity to specific resources
177 • Type of production system

- Availability of activity data (i.e. farm input and output information)- presence and quality of data related to specific farming practices
- Local scientific evidence- research conducted in the specific region related to mitigation
- Environmental regulation refers to policies governing environmental impacts.
- Market conditions - economic factors affecting livestock production

Similar to O'Brien et al. (2014), these criteria were used to select mitigation measures for assessment in this study. Mitigation measures tested in farms outside of Ireland were excluded as the abatement potential and the costs of measures are known to depend on the local environmental and economic context (Pellerin et al., 2017). Therefore, mitigation measures were restricted to scientific studies completed in Ireland. A literature review was conducted to identify mitigation measures that would be suitable for the Irish setting. It is important to understand that not every mitigation strategy will perfectly fit each farm's particular structures and conditions. Each farm runs under unique circumstances, such as differing soil types, climates, and resource availability, which might affect the applicability and efficacy of particular mitigation methods. For instance, certain mitigation strategies could work better than others in areas with heavy rainfall. This review yielded several measures for decreasing emissions from livestock farming. These mitigation measures were carefully examined and filtered based on the availability of financial information, farm activity data, and the feasibility of implementation (Table 2). The measures selected from this process for the case study farms were:

1. Animal productivity: The productivity of the herd was improved by breeding dairy heifers and cows to top sires in the economic breeding index (EBI). The EBI measures the

profitability of dairy sires across multiple genetic traits: production, fertility, health, etc. It was increased by an average of €15/cow per year for the bottom one-third of farms, €12/cow per year for the middle one-third and €9/cow per year for the top one-third of farms. Selecting the best sires from this index increased fat and protein yield by 5%-10% without impairing health or fertility. Extra supplements were fed, where necessary, to meet the herd's additional energy requirements for milk production.

2. Grass production and utilisation: The least productive pastures on a farm were targeted for renewal, i.e. reseeding. These swards were generally old, ten years or more, and contained the least amount of perennial ryegrass. To improve these swards, the annual reseeding rate was increased from 3% to 6% of the grassland area to the recommended rate i.e. 10%-15%. A similar rate of increase was assumed for each group of dairy farm (i.e. 5 to 6 percentage points).Grazing and silage swards were renewed with the best ryegrass cultivars in the pasture profit index (PPI; Teagasc, 2014). The most suitable cultivars in the PPI were 25%-30% more responsive to N than old pastures and improved the digestibility of forage by 50-60 g/kg DM. Fertiliser rates for establishing new swards were based on Teagasc recommendations (Wall & Plunkett, 2020).
3. Better reproductive management: The delays in age at first calving for replacement dairy animals was overcome by mating heifers to easy-calving sires when they were about 14-15 months old. Heats were closely monitored with simple detection aids, and heifers were vaccinated prior to the commencement of the breeding season. Both changes reduced age at first calving by 2 months for the middle one-third of dairy farms and by 5 months for the bottom one-third of farms. Replacement heifers typically calved between 22-26 months of age.

4. Early calving: The mean calving date for dairy and cattle rearing systems was brought forward by 2-weeks to early, mid and late February for the top, middle and top third of dairy farms, respectively,. Ninety percent of cows calved over a 6-week period. The breeding season was restricted to 12-weeks to tighten the calving pattern. Calving early in spring better synchronised the turnout of cows with grass supply, which decreased grass silage requirements by 35 to 45 kg DM/cow for the housing period. It also decreased concentrate supplementation by 16 to 28 kg DM/cow.
5. Reduce crude protein: Energy intake is a major factor restricting the milk yield of dairy cows offered a grass-only diet. Concentrate feedstuffs are offered to cows to overcome this restriction and to stretch feed reserves in spring and autumn. During the grazing season, the ration of dairy cows usually contains more than sufficient levels of crude protein (CP). The protein content of this ration was manipulated by replacing soybean meal with distillers' dried grains at a rate of 100 g/kg in concentrate compounds offered to grazing cows. This change decreased the crude protein content of concentrate supplements from 16% to the recommended level (14%) and had no impact on milk production.
6. Decrease fertiliser N: In line with climate policy for the Irish agricultural sector (GOI, 2023), the annual input of fertiliser N was reduced by 20%. Herbage yield was adjusted downwards by 0.8 to 1.1 t DM/ha based on the expected response to fertiliser N. The yield response to fertiliser was estimated according to the approach of Hoekstra et al. (2020). Grass silage and concentrate feedstuffs were imported to fill the grass deficit.
7. Protected urea: Compound and straight N fertilisers were replaced with urea fertilisers protected with an effective inhibitor, e.g., NBPT or NPPT. This form of N replaced 90%, 93% and 96% of the total N fertiliser for the top, middle and bottom dairy cohorts,

248 respectively. Phosphorus, K and other nutrients were supplied with zero N fertilisers,
249 e.g., 0-7-30.
250 8. White clover: Pastures dominated by productive grass species, e.g., perennial
251 ryegrasses, were converted to grass-white clover (GWC) swards. The legume was
252 introduced into grassland according to the steps outlined in the Teagasc management
253 guides (Hennessy et al., 2021). Grass-white clover swards were sown on 10%-15% of the
254 farm in spring once soil temperature was suitable for germination. Swards received 30-
255 40 kg P/ha and 60-90 kg K/ha at sowing to aid establishment. Fertiliser N was applied to
256 established GWC swards in spring and mid-autumn (September). The rate of application
257 depended on the stocking rate. The average white clover content of the sward increased
258 from less than 5% to between 20% and 25%, which resulted in fertiliser N decreasing by
259 74 to 92 kg/ha.
260 9. Slurry tank cover: Covers were installed on above and belowground tanks for cattle
261 slurry. The type of cover used was flexible and comprised of floating materials. Existing
262 storage tanks were retrofitted with flexible covers, as they are as effective as rigid
263 covers. They are also a more straightforward engineering solution. Storage tank covers
264 increased the amount of slurry N available for application, which replaced 1 to 2 kg of
265 fertiliser N/ha. Savings in fertiliser N were estimated using the approach described by
266 (Buckley & Krol, 2020).
267 10. Low emission slurry spreading (LESS) machinery: Cattle slurry was applied with vacuum
268 tankers fitted with LESS technology instead of conventional broadcasting equipment, i.e.
269 splash plate. The LESS equipment selected, the trailing shoe, delivered slurry onto the
270 soil in narrow bands, which reduced the surface area exposed to air compared to
271 broadcasting. This technology was fully adopted. It replaced 16%, 35% and 49% of the

slurry applied with a splash plate on the top, middle and bottom one-third of farms. This resulted in better N recovery from organic fertiliser, assumed to replace fertiliser N. The fertiliser replacement value of slurry spread with a trailing shoe was determined using the approach of Wall and Plunkett (2020).

The financial costs and benefits, and approaches applied to simulate the abatement potential of the aforementioned mitigation measures are detailed in the description in Table 2, along with references. Mitigation measures were implemented as stand-alone changes on case study dairy farms and applied as a whole to account for potential interactions between measures.

Modelling abatement

The abatement potential of mitigation measures was modelled over a 10-year period (2021 to 2030). A static approach was adopted to model abatement potential, where production levels on dairy farms were held constant over the period i.e. dynamic adjustments that farmers might adopt were not considered. This assumption indicates that enteric methane emissions remain relatively constant throughout the ten-year period, assuming a consistent feed conversion efficiency. Mitigation measures were fully implemented on the case study farms. Positive feedback loops between economic performance and farm activity were not considered for measures that improved productive efficiency. Agricultural input(lists these inputs) and output prices were forecasted after 2021 with CSO price indexes. The value of milk increased by an average of 1% per year, and input costs went up by 0.1%-0.2% on average. The figures were based on the trend in national prices between 2015 and 2021.

294 *Emission computations*

295 Gaseous emission and bio-economic models described in Herron et al. (2021a, b) for
296 dairy farms were combined to quantify the cost-effectiveness of mitigation measures. In
297 brief, these models compute emissions and environmental impacts associated with cattle
298 production systems according to the life cycle assessment (LCA) methodology. The
299 boundary of the emission models extends from the extraction of raw material to the sale of
300 dairy and beef products from the farm, i.e. cradle to farm-gate. For this analysis, gaseous
301 emission models were adapted to consider only agricultural sources of emissions that arise
302 within national inventories and the perimeter of a dairy farm. In other words, the national
303 inventory method (NIM) for simulating emissions from the agricultural sector was applied at
304 a farm scale. The term "national inventory methods" refers to the Intergovernmental Panel
305 on Climate Change (IPCC) protocols used by nations to calculate and report GHG emissions
306 and carbon dioxide (CO2) removals from the atmosphere. The specific emission sources
307 attributed to livestock farms with this method are agricultural soils, manure management,
308 and enteric fermentation. The NIM was deployed within the models to calculate NH_3 loss
309 and the primary GHG emissions, namely CO_2, methane, and nitrous oxide. These gaseous
310 losses were quantified as described by Herron et al. (2021a, b) with emission factors from
311 the Irish national inventory (Duffy et al., 2022) and emission data from the NFS (Dillon et al.,
312 2021). The tiers in the NIM classification system for emission estimation methodologies are
313 defined based on the level of detail, where higher tiers indicate a more accurate approach
314 to estimating emissions. Emission estimations specific to Irish livestock farms, classified as
315 tier-2 in the NIM, were used to quantify NH_3 and CH_4 emissions from manure management.
316 Ammonia and N_2O emissions related to spreading synthetic fertilisers in agriculture and N_2O
317 from manure deposited by grazing cattle were determined using tier 2 emission estimations.

For the remaining sources, default tier 1 emission factors reported in emission inventory guidelines (EEA, 2019; IPCC, 2019) were used to estimate ammonia and GHG emissions. The gaseous emission models converted GHG to CO_2 equivalents (CO_2-e) based on their 100-year global warming potential using factors from the IPCC (2013): CO2 = 1, CH4 = 28 N2O = 265. Gaseous emission models operated on a monthly time-step and reported annual NH_3 and GHG on a per-hectare basis. The impact of each mitigation measure on annual emissions was simulated for each case study farm and compared to the base situation (without measures).

Economic analysis

Standard economic metrics, i.e. gross output, gross profit, and net profit or loss, were determined using financial records collected on livestock farms for the period 2019-2021. Monthly receipts for milk, livestock, and forage sales were added to quantify the gross output or revenue of a farming system on a yearly basis. Gross profit or loss was measured as gross output less the variable cost of production. Consumables items, e.g., feedstuffs, fertilisers, lime, livestock, and medicines, were included in the variable cost category, as well as service costs for providers of materials and skills, e.g.agricultural contractors and veterinarians. Fixed costs were added to variable costs to determine the total cost of production. The expenses included under fixed costs were maintenance fees for buildings and machinery, depreciation, causal labour charges, electricity, telephone, insurance, and sundry expenses. Fixed costs were taken from gross margin to determine net profit or loss. This financial metric, along with gross profit or loss and gross output, were related to the area and outputs of livestock systems.

340 Marginal costs related to the abatement of gaseous emissions were determined for each
341 mitigation measure applied on livestock farms. Technical information from research studies
342 and price data from agricultural handbooks and national databases were used to derive
343 marginal abatement costs. The agricultural input and output prices considered in the
344 analysis were forecasted beyond 2021 using the aforementioned CSO price trend observed
345 between 2015 and 2021. For each abatement measure, the marginal cost was computed by
346 taking the financial benefits, i.e. cost saving and income gains of a measure from the extra
347 capital, maintenance, and running costs incurred. Financial costs and benefits were
348 converted to net present value (NPV) by annualising them over a 10-year period and
349 discounting at a rate of 4% per year (Equation 1),

350 $$\sum_{t=0}^{n} \frac{Cost_t - Benefit_t}{(1+r)^t} \quad (1)$$

351

352 Where $Cost_t$ is the additional cost of the measure in year t, $Benefit_t$ is the revenue or
353 cost-saving benefit in year t, r is the discount rate, and t is the time in years. The NPV for
354 each abatement measure was related to the quantity of GHG avoided in CO_2-e. Individual
355 measures were then categorised based on their costs. Three cost categories were defined:
356 1) cost beneficial, 2) cost effective, and 3) cost prohibitive. Practices and technologies that
357 simultaneously improved financial margins and reduced emissions were termed cost
358 beneficial. Mitigation measures that cost less than the shadow price of carbon or NH_3 were
359 considered cost effective, and measures above these prices were categorised as cost
360 prohibitive. The shadow carbon price was estimated at €50/t CO_2-e (Lanigan et al., 2019)
361 and the shadow price of NH_3 was €17.5/kg (Bruyn et al., 2018). Total abatement costs for a

livestock system were quantified by estimating the costs of implementing several mitigation measures simultaneously.

Sensitivity Analysis

The sensitivity of the case study farms' mitigation costs to major changes in economic conditions was tested using national statistics on agricultural prices (CSO, 2022). The output prices and the prices of major agricultural inputs i.e. fertiliser, feed, fuel, buildings and machinery were increased to the extreme levels observed in 2022. The annual rate of increase in input costs was also increased from an average of under 0.2% to 5% (Buckley et al., 2023). Output prices were not assumed to match the general rate of inflation, increasing by an average of 2% per annum. For the NPV of investments, the discount rate was changed from 4% to 8%.

Results and Discussion

GHG mitigation potential

Over the 10-year commitment period, the cumulative GHG abatement potential of standalone (implemented on their own) measures for dairy farms ranged from an average of 2.0 t CO_2-e/ha per year for the top one-third of farms to 2.8 t CO_2-e/ha per year for the bottom one-third of farms (Figures 1a-1c). Similar to MacLeod et al. (2010) and Lanigan et al. (2019) MACC analyses of agricultural GHG emissions, the majority (54%-86%) of the abatement potential on dairy farms could be realised with cost beneficial and net-zero cost measures. Cost savings were greatest for the bottom one-third of dairy farms, followed by the middle and top one-third of farms. Regarding the cost-effectiveness of GHG mitigation measures, there was little difference between the three groups of dairy farms. Cost-effective measures constituted 89% of the GHG mitigation potential for the top one-third, 90% for the middle one-third, and 93% for the bottom group. Cost-prohibitive measures

386 accounted for a greater share of the aggregated GHG abatement potential on the top third
387 of dairy farms than the middle or bottom groups. They tended to be technological
388 interventions (Figure 1a-1c).

389 The bulk of the benefit in terms of costs and GHG mitigation on dairy farms resulted from
390 animal and feed-related improvements. These measures increased productive efficiency,
391 decreasing the intensity of livestock production's emission by improving the input-to-output
392 ratio (Capper et al., 2009; Wiedemann et al., 2015). The main reason that the abatement
393 potential was lower for the top one-third of farms than the middle and bottom one-third of
394 farms was this group operated at a relatively high efficiency level. Reducing the CP content
395 of concentrate supplements offered to grazing cows was the most cost-beneficial way (i.e.
396 first measure) to mitigate GHG emissions from dairy farm . This mitigation measure
397 decreased feed costs and N excretion during the grazing season, without impairing animal
398 performance. Decreasing N excretion reduced gaseous emissions from soils, roadways and
399 collecting yards. Coupling emission reductions from these sources with feed cost savings
400 resulted in the CP reduction measure having the lowest GHG mitigation costs (-€513 to
401 €530/t CO2-e).

402 Improving grass utilisation and productivity by increasing reseeding rates to the
403 recommended levels, i.e. 10%-15% of the farm/year was the second most cost beneficial
404 mitigation measure in terms of GHG emissions. The abatement cost for this practice change
405 was between €328 and €345/t CO2-e and t resulted in more digestible forage, which
406 decreases methane emissions associated with the digestion of feed by ruminants (IPCC,
407 2019). Additionally, productive ryegrass swards respond better to fertiliser N and thus
408 reduce the likelihood of nitrous oxide losses from agricultural soils. Unlike the CP and grass

409 utilisation measures, the financial ranking of other feed and animal-related GHG mitigation
410 measures tended to vary across dairy farms. Early calving was the third most cost-beneficial
411 for the bottom and middle dairy groups but ranked fourth for the top group of farms.
412 Likewise, animal performance ranked as the third best measure in terms of costs for the top
413 group but was the fourth best option for the middle and bottom groups. All of these results
414 are based on the assumptions of unchanged animal numbers.

415 Some feed and technology-related mitigation measures shifted from cost-beneficial to
416 cost prohibitive in the GHG MACCs for dairy farms (Figures 1a-1c). Protected urea and white
417 clover were cost-beneficial or cost saving for the bottom and middle third of dairy farms (-
418 €22 to -€63 t/CO_2-e) and cost prohibitive for the top third (€35 to €36 t/CO_2-e). The
419 heterogeneity in costs for these mitigation measures was largely explained by the quantity
420 and type of replaced fertiliser. For the bottom and middle dairy groups, protected urea and
421 white clover primarily substituted CAN, but urea was the main fertiliser replaced for the top
422 dairy group. Urea fertiliser is generally cheaper than CAN and protected urea per unit of N
423 (CSO, 2022). Thus, replacing it with protected urea increased fertiliser costs for the top
424 group. Fertilizer expenditures for the top group were significantly reduced for white clover
425 when 38% to 40% of the N was replaced with biological N that is carbon neutral. However, it
426 was insufficient to outweigh the greater establishment costs for the top dairy group. Similar
427 replacement of fertiliser N by white clover for the middle and bottom dairy groups led to
428 greater savings in fertiliser costs because CAN was primarily replaced instead of urea. These
429 savings more than compensated the rise in establishment costs for white clover and thus
430 resulted in white clover being cost-beneficial for the bottom and middle dairy groups.

Decreasing fertiliser N was the most cost prohibitive option for each dairy farm group, ranging from €175 to €242/t CO2-e. This measure partly replaced a relatively inexpensive form of forage, grazed pasture, with a more expensive form, grass silage. Consistent with O'Donovan et al. (2021), the cost of producing grass silage was 2 to 2.5 times greater than grazed grass. Technologies to mitigate GHG emissions from manure also increased production costs and were consistently cost prohibitive for the LESS measure. Covering slurry tanks was generally cost effective, with GHG mitigation costs varying from €39 to €44 t/CO_2-e. Applying all GHG mitigation measures simultaneously on dairy farms was cost-beneficial. Financial savings were similar for each dairy group, averaging -€284 to -€274 t CO2-e. Generally, mitigation measures had synergistic relationships; combining them increased GHG abatement. However, abatement potentials for GHG mitigation measures were not additive. Interactions among measures, on average, decreased the annual GHG mitigation potential for all of the measures applied to 1.7 t CO_2-e/ha, 1.8 t CO_2-e/ha and 1.4 t CO_2-e/ha for the bottom, middle and top dairy groups, respectively. The existence of interactions between mitigation measures agrees with previous MACC analyses, e.g. Eory et al. (2018) and Wagner et al. (2015). Both authors highlighted the importance of accounting for interactions to give a more accurate estimate of the total GHG mitigation potential (Table 3).

Overall, combining mitigation measures decreased GHG emissions by 23%, 19% and 12% below 2020 levels for the bottom, middle and top dairy groups, respectively. For the bottom and middle one-third of dairy farms, this level of GHG mitigation potential was in line with the current emission ceiling put on the Irish agricultural sector. Under the Climate Action Plan 2023, agriculture needs to decrease GHG emissions by 10% by 2025 and 25% by 2030 to meet its emission ceiling targets, with 2020 as the base year (GOI, 2023). Based on our

455 analysis, the top group of dairy farms will need help to achieve the latter target with existing
456 technologies and practices. Further accelerating improvements in productive efficiency may
457 address some of the GHG mitigation gaps for this cohort. However, more is needed to meet
458 the 2030 and future GHG reduction targets, e.g., climate neutrality by 2040 or 2050.
459 Therefore, new mitigation measures must be developed and/or deployed on the top dairy
460 group and the bottom and middle third of farms. Developing strategies to reduce GHG
461 emissions from livestock should focus on the principal emission sources, mainly methane
462 from the enteric fermentation of feed in ruminants (Hristov et al., 2013). Dietary
463 supplements that inhibit methane, such as 3-NOP and halides, are promising mitigation
464 options (Cummins et al., 2022) that are likely to aid the sector in meeting medium-term
465 targets. Our study excluded these due to insufficient data to draw firm conclusions for grass-
466 based systems. Offsetting of GHG emissions will also be needed to achieve the sector's long-
467 term net-zero emission goals. Several practices are reported to offset GHG emissions via
468 enhancing carbon stocks in soils and vegetation (Soussana et al., 2010), but modelling these
469 practices with appropriate biogeochemical models was outside the scope of this study.

470 *Ammonia mitigation potential*

471 Consistent with the GHG MACC analyses for dairy farms, the bulk of NH_3 mitigation
472 potential was achieved with cost beneficial measures (Figures 2a-2c). The share of the
473 cumulative NH_3 abatement potential of cost beneficial or saving measures varied from 83%
474 for the top third of dairy farms to 87% for the bottom group of farms. For the top dairy
475 group, all of the mitigation measures examined were below the estimated price of NH_3 and,
476 therefore, cost effective. As regards the middle and bottom dairy groups, all but one of the
477 NH_3 mitigation measures, decreasing fertiliser N, were categorised as cost effective. Buckley
478 & Krol (2020) and Wagner et al. (2015) results generally corroborated our findings about the

cost-effectiveness of NH_3 mitigation measures. However, the ranking of NH_3 mitigation measures varied between studies and farm groups. For the middle and top dairy groups, improving grass utilisation and productivity was the most cost beneficial measure for reducing NH_3. Still, for the bottom group, white clover was slightly more cost beneficial. Improving animal performance was the second best option in terms of NH_3 mitigation costs for the middle and top third of dairy farms and ranked third for the bottom group. Early calving reduced mitigation cost as well and followed better animal performance in the cost rankings for each dairy group.

White clover ranked fourth in terms of cost saving for the middle group of dairy farms (-€17.1/kg NH_3 but shifted to cost positive for the top dairy group (€0.3/kg NH_3). The reasons for the fluctuation in costs for this measure were the same as described for the GHG MACC analysis, i.e. white clover primarily replaced a cheaper form of fertiliser N for the top dairy group compared to the other dairy groups. Differences in the type of fertiliser N replaced also caused protected urea to fluctuate between cost beneficial and cost positive. Better reproduction was a more cost effective option than protected urea, albeit it was not an option for the top third as this group were already calving all replacement heifers at 24 months of age. Decreasing the CP content of concentrate feed was a cost beneficial NH_3 mitigation for dairy farms (-€14.9 to -€17.3/kg NH_3). Ammonia mitigation costs for the CP reduction measure were similar to Buckley & Krol (2020). However, in contrast to Buckley & Krol (2020), decreasing the CP content of dairy diets ranked among the least cost beneficial mitigation measure for the bottom, middle and top third of farms. The difference in ranking was partly due to the mitigation measures examined, e.g. early calving and better grass utilisation were not considered by Buckley & Krol (2020). The discrepancy may also have been caused by different reductions in the crude protein content of diets and applying the

503 reduction at alternative times of the year, such as only during grazing season for this
504 analysis.

505 Combining mitigation measures over the period resulted in the total NH_3 abatement
506 potential ranging from an average of 9.9 kg NH_3/ha per year for the bottom third of farms to
507 12.0 kg NH_3/ha per year for the middle third. For the top third, the total NH_3 abatement
508 was, on average, 31 kg NH_3/ha per year. The disproportionate potential to abate NH_3 losses
509 from the top dairy group was caused by the more significant amount of urea applied on the
510 top third of farms relative to the other groups. Protecting this form of fertiliser N with
511 effective urease inhibitors substantially decreases NH_3 losses (Forrestal et al., 2016). This
512 measure accounted for about half of the NH_3 mitigation potential for the top dairy group.
513 Protected urea made a minor contribution to NH_3 mitigation potential for the bottom and
514 middle third of dairy farms as it primarily replaced CAN fertiliser instead of urea. The rate of
515 NH_3 loss from CAN application is similar to spreading urea with a urease inhibitor. Thus, the
516 potential emission savings were minor. LESS equipment had the greatest capacity to
517 mitigate NH_3 loss from the bottom and middle third of farms. However, its share of NH_3
518 mitigation potential was well below the 60% estimate of Buckley & Krol (2020) because a
519 large share (51%-84%) of the slurry was already applied with LESS in 2020 (base year).
520 Consequently, animal and feed-related measures were also essential contributors to NH_3
521 mitigation for dairy farms along with covering of slurry tanks. White clover was particularly
522 important for the top dairy group, but the NH_3 mitigation potential for this measure, like
523 protected urea, was sensitive to the form of fertiliser N it replaced. Substituting urea
524 fertiliser with CAN for the reference year led to white clover making a small (2% to 3%)
525 contribution to NH_3 mitigation for all dairy groups. It also decreased the mitigation potential
526 for the top group by 78% to 6.8 kg NH3/ha and increased GHG emissions. This observation

highlights the importance of examining gaseous emissions in an integrated way, as Wagner et al. (2015) reported.

The total NH_3 abatement potential, with interactions taken into account, for each dairy group exceeded the reduction targets currently set out in the national emission ceilings directive (European Commission, 2016) and was cost beneficial. The total cost of NH_3 abatement varied from €-34/kg NH_3 for the bottom third of farms to €-9/kg NH_3 for the top group. This finding somewhat supports the hypothesis that abatement costs rise as farm profitability increases, even though the measures were still cost saving. For the bottom and middle groups, NH_3 abatement was at the lower end of the range recommended by the CLRTAP for regions with high livestock densities and nearer to the upper end of the range for the top group. Replacing urea with straight CAN fertiliser in the base year resulted in all of the groups falling outside of the CLRTAP range. It also results in the top group having the least abatement potential for NH_3, which was more in line with the results for GHG abatement. None of the mitigation measures assessed for NH_3 led to greater GHG emissions or vice versa. This issue, known as pollution swapping, can be a problem for some mitigation measures, particularly those related to organic and inorganic N applications, as Buckley & Krol (2020) pointed out. The risk of pollution swapping is potentially increased by having separate policy instruments for mitigating air pollution and climate change. Combining these policies, as suggested by Wagner et al. (2015), and harmonising them would reduce this risk and help policymakers establish appropriate sectoral emission ceilings for NH_3 and GHG.

Sensitivity Tests

Rising input and output prices decreased GHG mitigation costs for each group of dairy farm (Table 4). For the bottom third of dairy farms, cumulative GHG mitigation costs

551 decreased from -€184 to -€294 t/CO_2-e. The decrease for the middle third of dairy farms
552 was -€110 t/CO_2-e and -€104/t CO_2-e for the top third of farms. Greenhouse gas mitigation
553 costs were lower for the bottom and middle third of farms compared to the top group. The
554 bulk of the benefit in terms of mitigation cost resulted from animal and feed related
555 measures. Technological measures also contributed, specifically protected urea. The cost
556 benefit of this technology was substantially greater than the initial analysis due to the two
557 and half to threefold rise in the cost of N fertilisers in 2022. This resulted in a larger price
558 differential between CAN and protected urea, and was the driver of the major decrease in
559 GHG mitigation costs for white clover. The rise in fertiliser costs also brought cost
560 prohibitive measures closer to the shadow price of carbon.

561 Consistent with GHG emissions, increasing prices to 2022 levels reduce NH_3 mitigation
562 costs across case study dairy farms. The reduction in cumulative NH_3 mitigation costs was
563 greatest for the bottom third of dairy farms, €-20.1/kg NH_3. Ammonia mitigation costs
564 decreased by a similar amount, €-16.6/kg NH_3, for the middle third of farms; the decrease in
565 NH_3 mitigation costs was substantially less for the top third of farms (€-4.8/kg NH_3). This can
566 be explained by the greater use of urea on these farms, which resulted in less cost savings
567 for protected urea or white clover compared to the other farms. For NH_3 and GHG
568 emissions, the steep increase in fertiliser price caused protected urea and white clover to
569 move from cost effective to cost beneficial for the top dairy group. The majority of NH_3
570 mitigation measures were cost beneficial or cost effective. In line with the initial analysis,
571 none of the selected NH_3 mitigation measures were cost prohibitive for the top dairy group
572 and the only cost prohibitive measure for the bottom and middle groups was decreasing
573 fertiliser N.

Limitations

The case study farms in this study only partially represent the agriculture industry. The findings discussed here are based on particular case studies and may not be generalisable to the farming industry. It is important to note that this assessment only offers an "average" representation and does not adequately consider the significant variety that distinguishes Irish farms. The national MACC provide a clear understanding and representation of mitigation costs. However, it is important to recognise that the depth of our study does not allow for a thorough examination of the relative costs, labour costs, or the particular costs related to implementing mitigation measures. It's crucial to emphasise that even if this paper offers various mitigation techniques, the adoption rate of these mitigation strategies is a limitation. Instead, this study emphasise the opportunity for mitigation, highlighting the significance of these choices in the larger context. It is critical to recognise that different farm management techniques might affect the success of certain mitigation strategies. For instance, modifications to crop rotation or irrigation practices may affect how well some mitigation measures work. The understanding of implementing new techniques and the readily available information affect farmers' decision-making processes on mitigating measures. Although the direct mitigation effects may be the main emphasis of this study, it is important to recognise the possible external advantages, such as changes in ecosystems and water quality, which call for consideration for future research projects. Farmers need a customised decision-support tool to help them determine which mitigation strategies are best for their type of farm, farm investment, and farm structure. Our analysis demonstrates the possibility for mitigation in three separate groups, the top, medium, and bottom third of Irish dairy farms.

In addition to these factors, it is crucial to understand that risk perception and management techniques can also have an impact on the success of mitigation strategies. Our research concentrated on a static assessment of farms at a particular moment and did not thoroughly assess dynamic feedback effects between pasture/feed availability, yield, and total production factors. These feedback loops may have a significant impact profitability. Further research may include dynamic programming models such as CPLEX to address this research question.

Conclusions

Farm-level MACCs are useful for understanding the capacity to reduce gaseous emissions from specific agricultural systems or farms. The approach illustrates that the potential to reduce GHG and NH_3 emissions from different farms varies significantly. It demonstrated that combining mitigation measures resulted in a decrease of 23%, 19%, and 12% in GHG emissions below 2020 levels for the bottom, middle, and top dairy groups, respectively. This implies the top dairy group will struggle to achieve its 2030 and future GHG reductions targets with existing technologies and practices. These findings clearly indicate that new GHG mitigation measures need to be developed for dairy farms. The knowledge generated by the farm-level MACC is useful because it enables advisors and livestock farmers to choose the most affordable mitigation strategies for achieving air quality and climate change goals. The approach highlights that some farms have greater potential for abatement than others and that the most economically effective mitigation measures vary by farm. Farm-level MACCs can account for variability in GHG and NH_3 mitigation potentials and costs that are often missed at the sectoral or country level. This suggests that the potential to mitigate GHG and NH_3 emissions from the agricultural sector is over or

620 underestimated and needs to be quantified with a more detailed approach at regional or
621 local scales.

622 **References**

623 Beaudor, M., Vuichard, N., Lathière, J., Evangeliou, N., Van Damme, M., Clarisse, L., &
624 Hauglustaine, D., 2023. Global agricultural ammonia emissions simulated with the
625 ORCHIDEE land surface model. Geosci. Model Dev. 16, 1053-1081.

626 Bord Bia, 2022. Performance and prospects report 2021/2022. Bord Bia, Pembroke Road,
627 Dublin 4, Ireland.

628 Bruyn, S. d., Bijleveld, M., Graaff, L. d., Schep, E., Schroten, A., Vergeer, R., & Ahdour, S.
629 (2018). Environmental Prices Handbook EU28 version. CE Delft. Retrieved on 7 December
630 2023 from https://cedelft.eu/wp-
631 content/uploads/sites/2/2021/04/CE_Delft_7N54_Environmental_Prices_Handbook_EU28_
632 version_Def_VS2020.pdf

633 Buckley, C., Krol., (eds) 2020. An analysis of the cost of the abatement of ammonia
634 emissions in Irish agriculture to 2030. Teagasc, Oak Park, Co. Carlow, Ireland.

635 Buckley, C., Dillon, E., Donnellan, T., Hanrahan, K., Houlihan, T., Kinsella, A., Lennon, J.,
636 Loughrey, J., McKeon, M., Moran, B., Thorne, F., 2023. Outlook 2023 – Economic prospects
637 for agriculture. Teagasc, Agricultural Economic and Farm Surveys Department, Athenry,
638 Co.Galway.

639 Burchill, W., Lanigan, G.J., Li, D., Williams, M., & Humphreys, J., 2016. A system N balance
640 for a pasture-based system of dairy production under moist maritime climatic conditions.
641 Agriculture, Ecosystems & Environment 220, 202-210.

642 Capper, J.L., Cady, R.A., & Bauman, D.E., 2009. The environmental impact of dairy
643 production: 1944 compared with 2007. Journal of Anim Science 87, 2160-2167.

644 Central Statistics office (CSO), 2022. Statistical databases and Farm Structures Surveys.
645 Central statistics office, Skehard Road, Mahon, Cork. Retrieved on 24 August 2022 from
646 https://www.cso.ie/en/databases/

647 Cummins, S., Lanigan, G.J., Richards, K.G., Boland, T.M., Kirwan, S.F., Smith, P.E., & Waters,
648 S.M., 2022. Solutions to enteric methane abatement in Ireland. Irish Journal of Agricultural
649 and Food Research. Retrieved on 3rd March 2023 from
650 https://www.scienceopen.com/hosted-document?doi=10.15212/ijafr-2022-0014

651 Department of Agriculture, Food and the Marine (DAFM), 2022. Annual review and outlook
652 for agriculture, food and the marine 2022. DAFM, Economic and Planning Division,
653 Agriculture House, Kildare street, Dublin 2. Ireland.

654 Duffy, P., Black, K., Fahey, D., Hyde, B., Kehoe, A., Monaghan, S., Murphy, J., Ryan, A. M., &
655 Ponzi, J., 2022. Ireland's national inventory report 2022: Greenhouse gas emissions 1990-

2020 reported to the United Nations Framework Convention on Climate Change. Environmental Protection Agency, Johnstown Castle, Co. Wexford.

Dillon, E., Donnellan, T., Moran, B.,& Lennon, J., 2021. Teagasc National Farm Survey 2020 results. Teagasc, Agricultural Economics and Farm Surveys Department, Athenry, Co. Galway, Ireland.

Eory, V., Pellerin, S., Carmona Garcia, G., Lehtonen, H., Licite, I., Mattila, H., Lund-Sørensen, T., Muldowney, J., Popluga, D., Strandmark, L., & Schulte, R., 2018. Marginal abatement cost curves for agricultural climate policy: State-of-the art, lessons learnt and future potential. Journal of Cleaner Production 182, 705-716.

European Commission, 2016. Directive 2016/2284 of the European parliament and of the council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC. Official Journal of the European Union 59, 83-92.

European Environment Agency (EAA), 2019. EMEP/EEA air pollutant emission inventory guidebook 2019. Technical guidance to prepare national emission inventories. Publications office of the European Union, Luxembourg.

European Commission, Directorate-General for Agriculture and Rural Development, Peyraud, J., MacLeod, M., Future of EU livestock – How to contribute to a sustainable agricultural sector ? – Final report, Publications Office, 2020, https://data.europa.eu/doi/10.2762/3440

Farm and forestry contractors in Ireland (FCI), 2021. Contractor charges guide 2021. FCI, Portlaoise enterprise centre, Portlaoise, Co. Laois, Ireland. Retrieved on 2nd March 2022 from https://www.farmcontractors.ie/

Food and Agriculture Organisation of the United Nations (FAO), 2009. The state of food and agriculture: Livestock in the balance. FAO, Vialle delle Terme di Caracalla, Rome, Italy.

Food and Agriculture Organisation of the United Nations (FAO), 2018. World livestock: Transforming the livestock sector through the sustainable development goals. FAO, Rome, Italy.

Forrestal, P.J., Harty, M., Carolan, R., Lanigan, G.J., Watson, C.J., Laughlin, R.J., McNeill, G., Chambers, B.J., Richards, K.G., 2016. Ammonia emissions from urea, stabilized urea and calcium ammonium nitrate: insights into loss abatement in temperate grassland. Soil Use and Management 32, 92-100.

Gerber, P.J, Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falucci, A., &Tempio, G., 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. FAO, Rome, Italy.

Government of Ireland (GOI), 2023. Climate action plan 2023: Securing our future. Department of Environment, Climate and Communications, Adelaide Road, Dublin 2, Ireland.

694 Harty, M.A., Forrestal, P.J., Watson, C.J., McGeough, K.L., Carolan, R., Elliot, C., Krol, D.,
695 Laughlin, R.J., Richards, K.G., Lanigan, G.J., 2016. Reducing nitrous oxide emissions by
696 changing N fertiliser use from calcium ammonium nitrate (CAN) to urea based formulations.
697 Science of the Total Environment 563-564, 576-586.

698 Henchion, M., Hayes, M., Mullen, A.M., Fenelon, M., Tiwari, B., 2017. Future Protein Supply
699 and Demand: Strategies and Factors Influencing a Sustainable Equilibrium. Foods 6, 53.

700 Hennessy, D., O'Donovan, M., Creighton, P., Egan, M., McCarthy, B., 2021. Moorepark Dairy
701 levy research update, series 38. Management and establishment of grass-clover swards.
702 Teagasc, Animal and Grassland Research and Innovation, Moorepark, Fermoy, Co. Cork.

703 Herron, J., Curran, T.P., Moloney, A.P., McGee, M., O'Riordan, E.G., O'Brien, D., 2021a. Life
704 cycle assessment of pasture-based suckler steer weanling-to-beef production systems:
705 Effect of breed and slaughter age. Animal 15, 100247.

706 Herron, J., Hennessy, D., Curran, T., Moloney, A., O'Brien, D., 2021b. The simulated
707 environmental impact of incorporating white clover into pasture-based dairy production
708 systems. Journal of Dairy Science 104, 7902-7918.

709 Hoekstra, N.J., Schulte, R.P.O., Forrestal, P.J., Hennessy, D., Krol, D.J., Lanigan, G.J., Müller,
710 C., Shalloo, L., Wall, D.P., Richards, K.G., 2020. Scenarios to limit environmental nitrogen
711 losses from dairy expansion. Science of the Total Environment 707, 134606.

712 Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S.,
713 Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B., Tricarico, J.M., 2013. SPECIAL
714 TOPICS — Mitigation of methane and nitrous oxide emissions from animal operations: I. A
715 review of enteric methane mitigation options. Journal of Animal Science 91, 5045-5069.

716 Hyde, B., Duffy, P., Ryan, A. M., Murphy, J., Fahey, D., Monaghan, S., Kehoe, A., 2022.
717 Ireland informative inventory report 2022: Air pollutant emissions in Ireland 1990-2020
718 reported to the secretariat of the UNECE convention on long-range transboundary air
719 pollution and to the European Union. Environmental Protection Agency, Johnstown Castle,
720 Co. Wexford.

721 Intergovernmental Panel on Climate Change (IPCC), 2013. Climate Change 2013: The
722 physical science basis. Contribution of working group I to the fifth assessment report of the
723 Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge,
724 United Kingdom and New York, USA.

725 IPCC, 2019. 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas
726 inventories. Volume 4: Agriculture, forestry and other land use. Institute for Global
727 Environmental Strategies (IGES), Hayama, Japan.

728 Jones, A.K., Jones, D.L., Cross, P., 2015. Developing farm-specific marginal abatement cost
729 curves: Cost-effective greenhouse gas mitigation opportunities in sheep farming systems.
730 Land Use Policy 49, 394-403.

731 Lanigan, G., Donnellan, T., (eds.) 2019. An analysis of abatement potential of greenhouse
732 gas emissions in Irish agriculture, 2020-2030. Teagasc, Crops, Environment and Land Use
733 Programme, Oak Park, Co. Carlow.

734 Ma, R., Li, K., Guo, Y., Zhang, B., Zhao, X., Linder, S., Guan, C., Chen, G., Gan, Y., Meng, J.,
735 2021. Mitigation potential of global ammonia emissions and related health impacts in the
736 trade network. Nature Communications 12, 6308.

737 MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S.,
738 Wall, E., McVittie, A., Pajot, G., Matthews, R., Smith, P., Moxey, A., 2010. Developing
739 greenhouse gas marginal abatement cost curves for agricultural emissions from crops and
740 soils in the UK. Agricultural Systems 103, 198-209.

741 Markiewicz-Keszycka, M., Carter, A., O'Brien, D., Henchion, M., Mooney, S., Hynds, P., 2023.
742 Pro-environmental diversification of pasture-based dairy and beef production in Ireland, the
743 United Kingdom and New Zealand: a scoping review of impacts and challenges. Renewable
744 Agriculture and Food Systems 38, e5.

745 O'Brien, D., Shalloo, L., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Hanrahan, K., Lalor,
746 S., Lanigan, G., Thorne, F. and Schulte, R., 2014. An evaluation of the effect of greenhouse
747 gas accounting methods on a marginal abatement cost curve for Irish agricultural
748 greenhouse gas emissions. Environmental Science & Policy, 39, pp.107-118.

749 O'Donovan, M., Hennessy, D., Creighton, P., 2021. Ruminant grassland production systems
750 in Ireland. Irish Journal of Agricultural and Food Research 59.

751 Organisation for Economic Co-operation and Development (OECD)/FAO, 2020. Agricultural
752 and food markets – Trends and prospects. In OECD-FAO, Agricultural Outlook 2020-2029,
753 OECD publishing, Paris.

754 Organisation for Economic Co-operation and Development (OECD)/FAO, 2021. Agricultural
755 and food markets – Trends and prospects. In OECD-FAO, Agricultural Outlook 2021-2030,
756 OECD publishing, Paris.

757 Otte, J., Costales, A., Dijkman, D., Pica-Ciamarra, U., Robinson, T., Ahuja, V., Ly, C., Roland-
758 Holst, D., 2012. Livestock sector development for poverty reduction: an economic and policy
759 perspective – Livestock's many virtues. Food and Agriculture Organisation of the United
760 Nations, Rome, Italy.

761 Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J.-P., Chenu, C., Colnenne-
762 David, C., De Cara, S., Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F.,
763 Hassouna, M., Hénault, C., Jeuffroy, M.-H., Klumpp, K., Metay, A., Moran, D., Recous, S.,
764 Samson, E., Savini, I., Pardon, L., Chemineau, P., 2017. Identifying cost-competitive
765 greenhouse gas mitigation potential of French agriculture. Environmental Science & Policy
766 77, 130-1

767 Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of
768 ruminant production systems through carbon sequestration in grasslands. Animal 4, 334-
769 350.

770 Teagasc, 2022. Teagasc National Farm Survey – Dairy enterprise factsheet 2021. Teagasc,
771 Agricultural Economics and Farm Surveys Department, Athenry, Co. Galway, Ireland.

772 Teagasc, 2014. Pocket manual for reseeding. Dairy Levy Research Update: Series 22.
773 Teagasc, Animal & Grassland, Research and Innovation, Moorepark, Fermoy, Co. Cork,
774 Ireland

775 United Nations Economic Commission for Europe (UNECE), 2021. Assessment report on
776 ammonia emissions. UNECE, Palais des Nations, Geneva, Switzerland. Retrieved on 6 April
777 2023 from https://unece.org/sites/default/files/2021-03/ECE_EB.AIR_WG.5_2021_7-
778 2102624E.pdf

779 United Nations, 2023. For a liveable: Net-zero commitments must be backed by credible
780 actions. Retrieved on 7 February 2023 from https://www.un.org/en/climatechange/net-
781 zero-coalition

782 United Nations Framework Convention on Climate Change (UNFCCC), 2023. The Paris
783 Agreement. Retrieved on 7 February 2023 from https://unfccc.int/process-and-
784 meetings/the-paris-agreement

785 Wagner, S., Angenendt, E., Beletskaya, O., Zeddies, J., 2015. Costs and benefits of ammonia
786 and particulate matter abatement in German agriculture including interactions with
787 greenhouse gas emissions. Agricultural Systems 141, 58-68.

788 Wall, D.P., Plunkett, M., 2020. Major and micro nutrient advice for productive agricultural
789 crops. Teagasc, Soils and Environment Centre, Johnstown Castle, Co. Wexford, Ireland.

790 Wiedemann, S.G., Henry, B.K., McGahan, E.J., Grant, T., Murphy, C.M., Niethe, G., 2015.
791 Resource use and greenhouse gas intensity of Australian beef production: 1981–2010.
792 Agricultural Systems 133, 109-118.

793

794 **Table 1.** General characteristics of the top, middle and bottom third of Irish dairy farm in
795 terms of economic performance[a], 2020-2021 (CSO, 2022; ICBF, 2022; Teagasc, 2022).

		Dairy		
Parameter	Unit	Top	Middle	Bottom
Grassland				
Area	Ha	56	56	48
Fertiliser N rate	kg N/ha	211	177	132
CAN	% fertiliser N	25	87	94
Urea	% fertiliser N	65	6	2
Protected urea	% fertiliser N	10	7	4
Fertilizer P rate	kg P/ha	16	12	11
LESS[a]	% of slurry	84	65	51
Grass utilisation	t DM/ha	10.4	8.0	5.9
Herd				
Cows	average hd[b]	119	92	61
Culling rate	% cows	18%	20%	22%
Replacement rate	% cows	19%	21%	24%
Age at first calving	Month	24	26	29
Mean calving date	Date	24-Feb	01-Mar	08-Mar
Grazing season – cows	Day	246	241	235
Concentrate feedstuffs	kg/LU[c]	1,140	1,223	1,154
Stocking rate	LU[c]/ha	2.52	2.07	1.72
Production				
Beef live weight	kg/ha	258	217	188
Milk yield	kg/cow	6,443	5,999	4,826
Milk fat and protein	kg/cow	493	455	396
Economic				
Gross output	€/ha	6,570	4,954	3,492
Variable costs	€/ha	2,140	1,812	1,451
Fixed costs	€/ha	1,790	1,365	1,168
Gross margin	€/ha	4,430	3,142	2,041
Net margin	€/ha	2,640	1,777	873

796 [a] Farms were ranked in terms of gross margin per hectare
797 [b] Low emission slurry spreading, e.g., trailing shoe.
798 [c] Livestock unit

Table 2. Technical summary of measures applied to mitigate gaseous emissions from livestock production systems in the Republic of Ireland.

Measure	Financial costs	Abatement potential
1. Animal productivity	Based on industry reports, picking top EBI sires increased the price of artificial insemination (AI) straw by €4 relative to average sires. Factoring in repeat inseminations added a further €2.80 to the cost of AI/dairy cow. Prices for compound concentrate feeds ranged from €300-350 t/DM (CSO, 2022).	Breeding better dairy cows diluted gaseous emissions. At farm-level, the emission benefits of dilution depended on base yields. The emission benefit was computed using the methods in Irish national inventories (Duffy et al., 2022; Hyde et al., 2022).
2. Grass production and utilisation	Establishment costs for reseeded swards were estimated using standard rates for materials and agricultural contractors (Teagasc, 2014; FCI, 2021). The total cost of establishing a new pasture was estimated to be €340/ha.	Improving pasture's response to fertiliser N reduced N emissions from soils. Improving sward digestibility mitigated CH_4 emissions from cattle. Emission reductions were determined based on the aforementioned national inventory methods.
3. Better reproductive Performance	A roll of scratch cards cost €100, and the adhesive price for the cards was €20. One roll was considered sufficient for 60 heifers throughout a breeding season. Vaccines for reproductive diseases cost €5/replacement heifer.	Reductions in gaseous emissions associated with the maintenance of breeding cattle were determined according to national inventory guidelines. (Duffy et al., 2022; Hyde et al., 2022).
4. Early compact calving	Identifying empty and late-calving cows via pregnancy scanning costs €4-€5/animal. Call-out charges for scanning ranged from €50-€60.	Grazing cattle had an 18-21% lower Ym factor than cattle indoors on grass silage-based diets (Hyde et al., 2022). They also had lower CH_4 and NH_3 emission factors for manure than housed cattle (Duffy et al., 2022).
5. Reduce crude protein	Concentrate compounds offered to cows at pasture were reformulated by substituting soybean meal with distillers' dried grain at a rate of 100 kg/t. This change decreased the price of concentrate compounds for grazing animals by about €11.5/t and reduced crude protein content by 2% point. Prices for concentrate ingredients were taken from industry reports.	Nitrogen intake and excretion rates for dairy cows were decreased in line with the drop in the crude protein of concentrate compounds. The knock-on effect of reductions in N excretion rates on NH_3 and GHG emissions was calculated according to the recommended inventory approaches via the adapted emission model of Herron et al. (2021b)

Measure	Financial costs	Abatement potential
6. Decrease fertiliser N	Silage production costs were based on O'Donovan et al. (2021). Transport and labour charges were included for importing silage along with feed out costs. In total, imported silage cost €231/t DM utilised. The price of concentrate feed varied from €300-€330 t/DM.	Reductions in fertiliser-related gaseous emissions were determined using country-specific loss factors from Irish emission inventories (Duffy et al., 2022; Hyde et al., 2022).
7. Protected urea	Prices for fertilisers were taken from national statistics (CSO, 2022). Per kg of N, CAN cost €1.04 and urea cost €0.83. Protecting urea with a urease inhibitor added €0.1 to the price of 1 kg of urea N.	Protected urea decreased N_2O loss by 73% relative to CAN and reduced NH_3 loss by 80% compared to straight urea (Duffy et al., 2022; Hyde et al., 2022).
8. White clover	The cost of establishing grass-white clover swards was €10-€15 greater per acre than ryegrass swards. Including white clover in the seed mix and oversowing it caused most of the rise in reseeding costs.	White clover had a similar mode of action as the measure decreasing fertiliser N. The approach described previously to calculate emission savings for decreasing fertiliser N was applied to determine the savings in emissions caused by replacing fertiliser N with N fixed by white clover.
9. Slurry tank cover	Material and fitting charges for flexible covers were taken from Reis et al. (2015). Charges were adjusted for the baseline year (2020). This brought the overall charge for tank covers to €1.65 per m3 of slurry stored.	The NH_3 emission factor for covered tanks was 62% less than for uncovered tanks (Van der Weerden et al., 2022). Methane and N_2O emission factors for covered tanks were based on inventory guidelines (IPCC, 2019). This method estimates that covering tanks reduces CH_4 emissions by 40%.
11. Low emission slurry spreading (LESS)	Spreading slurry with trailing shoe increased application costs by 31% to €89/hr (FCI, 2021). Cattle slurry was applied with a 2500 gallon vacuum tanker by agricultural contractors.	Ammonia loss related to spreading slurry in summer was reduced by 60% by switching from splash plate to trailing. For spring and autumn, the same change reduced NH_3 loss by 13%. Fertiliser N saved by trailing shoe reduced gaseous emissions associated with using this energy intensive input.

Table 3. Greenhouse gas (GHG) abatement potentials and mitigation costs for the bottom, middle and top third Irish dairy farms in the Teagasc national farm survey. Note: Farms were ranked in terms of gross margin/ha.

Mitigation Measure	GHG Abatement Potential (kg CO2-e/ha)			GHG Mitigation Costs (€/t CO2-e)		
	Bottom	Middle	Top	Bottom	Middle	Top
Improve animal performance	603	404	261	-194	-232	-321
Increase grass utilisation	412	485	522	-345	-332	-328
Crude protein	15	20	25	-530	-517	-514
Better reproduction	380	205	NA	-95	-93	NA
Early calving	147	199	284	-321	-326	-189
Decrease fertiliser N	195	249	214	186	175	242
Protected urea	366	454	154	-23	-22	35
White clover	503	369	249	-63	-30	11
Slurry tank cover	199	255	295	41	44	39
LESS	18	18	4	118	100	238
Total	1,709	1,805	1,389	-184	-185	-202

Table 4. Sensitivity of greenhouse gas (GHG) and ammonia (NH_3) mitigation costs for the bottom, middle and top third of Irish dairy farms in the Teagasc national farm survey to elevated agricultural input and output prices in 2022. Note: Farms were ranked in terms of gross margin/ha.

Mitigation Measure	GHG Mitigation Costs (€/t CO2-e)			NH_3 Mitigation Costs (€/kg NH_3)		
	Bottom	Middle	Top	Bottom	Middle	Top
Improve animal performance	-269	-312	-414	-58.1	-60.5	-59.0
Increase grass utilisation	-475	-432	-415	-69.7	-65.6	-69.0
Crude protein	-575	-562	-559	-16.1	-17.1	-18.7
Better reproduction	-149	-132	NA	-40.8	-20.9	NA
Early calving	-382	-388	-230	-45.5	-40.4	-32.4
Decrease fertiliser N	107	97	191	58.6	34.0	7.4
Protected urea	-157	-156	-104	-119.7	-37.6	-0.7
White clover	-251	-221	-213	-203.6	-124.6	-5.9
Slurry tank cover	29	32	27	3.7	3.8	2.8
LESS	124	68	397	0.7	0.4	6.3
Total (including interactions)	-294	-295	-306	-53.7	-44.5	-14.1

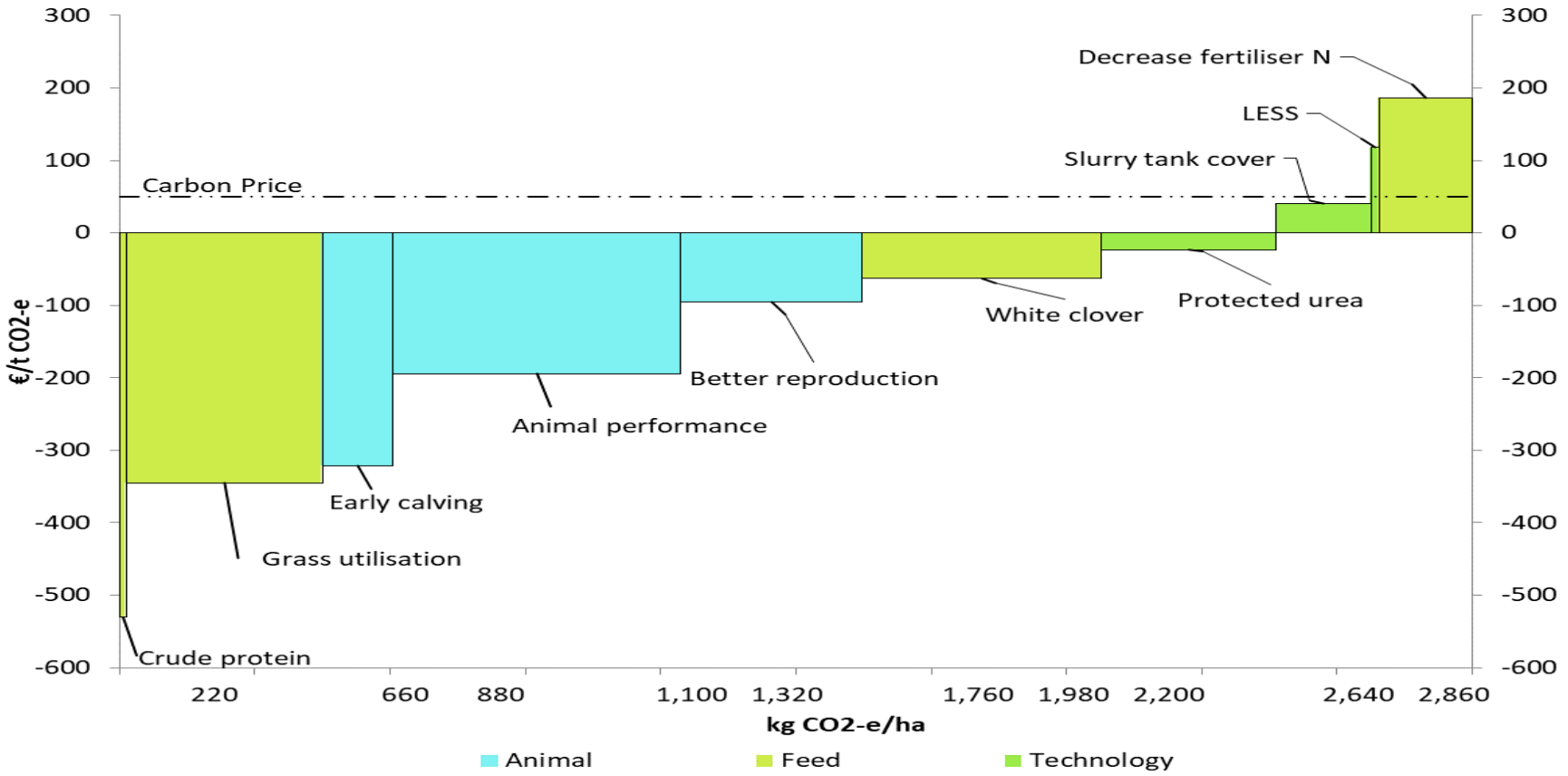

Figure 1a. Marginal abatement cost curve of greenhouse gas mitigation measures for bottom third of Irish dairy farms in terms of gross margin. Abatement potential corresponds to the annual average for the period 2021-2030. Colours indicate the type of mitigation measure. The dashed line represents the shadow price of carbon. The width of each block represents the total CO2 saving per annum of the Mitigation strategies. The height of the block shows the cost per unit of CO2 saved, over the lifetime of the project. Savings are shown as negative costs. These mitigation strategies that are cost prohibited are above the horizontal (x) axis, which means that they will require a net investment.

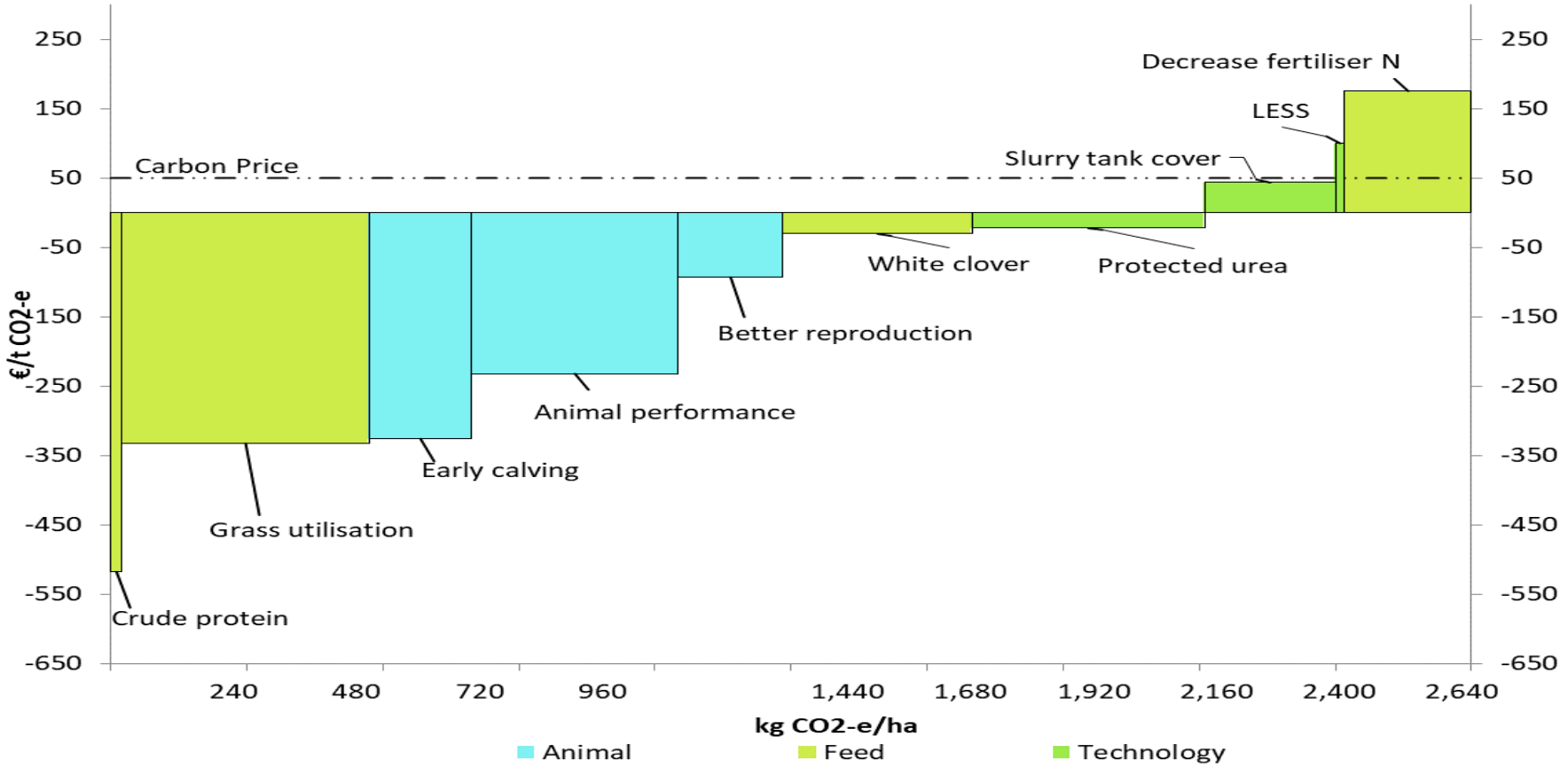

Figure 1b. Marginal abatement cost curve of greenhouse gas mitigation measures for middle third of Irish dairy farms in terms of gross margin. Abatement potential corresponds to the annual average for the period 2021-2030. Colours indicate the type of mitigation measure. 78% to 6.8 kg NH3/ha .The dashed line represent the shadow price of carbon. The width of each block represents the total CO2 saving per annum of the Mitigation strategies. The height of the block shows the cost per unit of CO2 saved, over the lifetime of the project. Savings are shown as negative costs. These mitigation strategies that are cost prohibited are above the horizontal (x) axis, which means that they will require a net investment

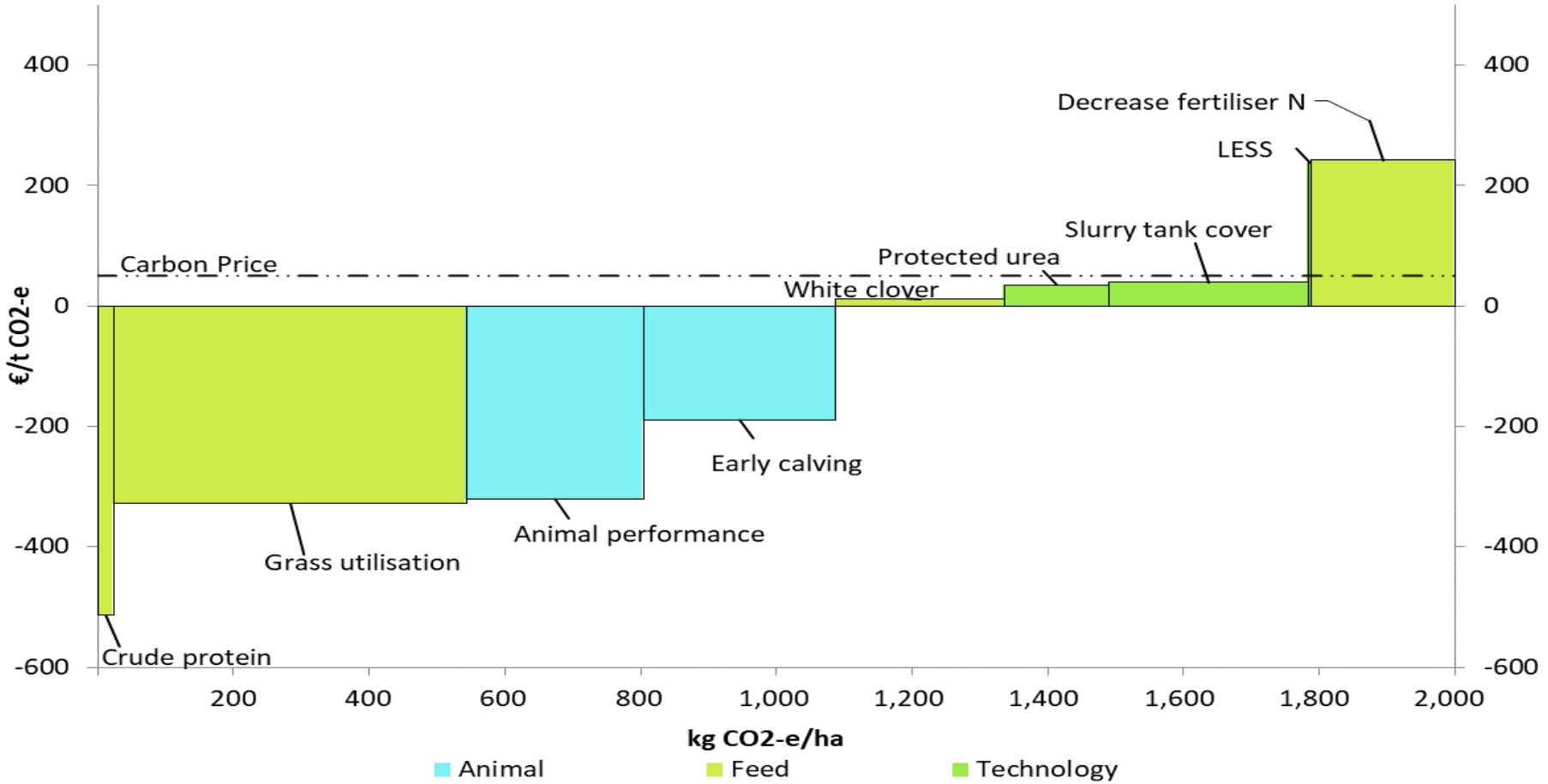

Figure 1c. Marginal abatement cost curve of greenhouse gas mitigation measures for top third of Irish dairy farms in terms of gross margin. Abatement potential corresponds to the annual average for the period 2021-2030. Colours indicate the type of mitigation measure. The dashed line represents the shadow price of carbon. The width of each block represents the total CO2 saving per annum of the Mitigation strategies. The height of the block shows the cost per unit of CO2 saved, over the lifetime of the project. Savings are shown as negative costs. These mitigation strategies that are cost prohibited are above the horizontal (x) axis, which means that they will require a net investment

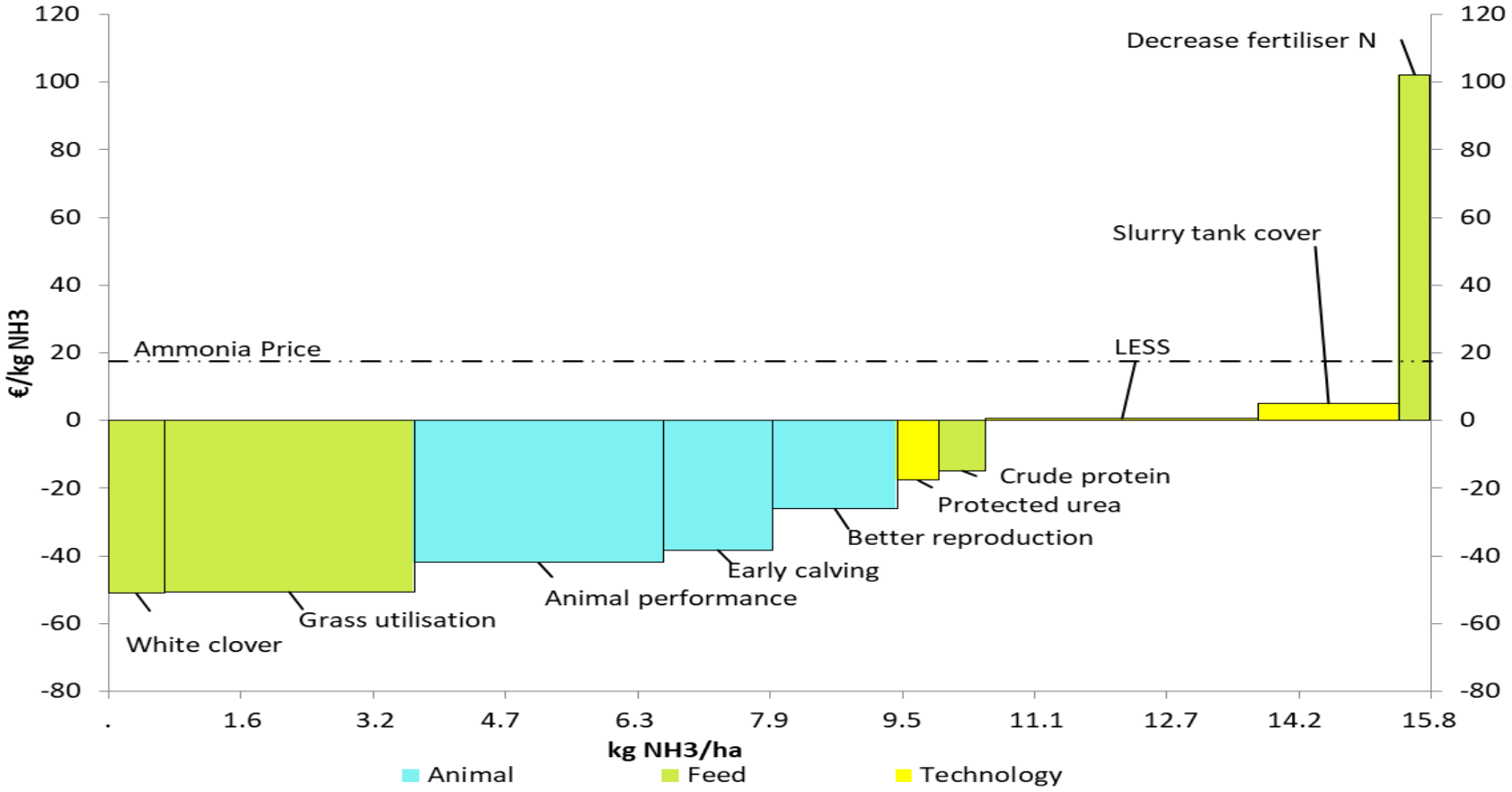

Figure 2a. Ammonia (NH_3) marginal abatement cost curve for the bottom third of Irish dairy farms in terms of gross margin. Abatement potentials correspond to the annual average for the period 2021-2030. Colours indicate the type of mitigation measure. The dashed line represents the shadow price of NH_3.

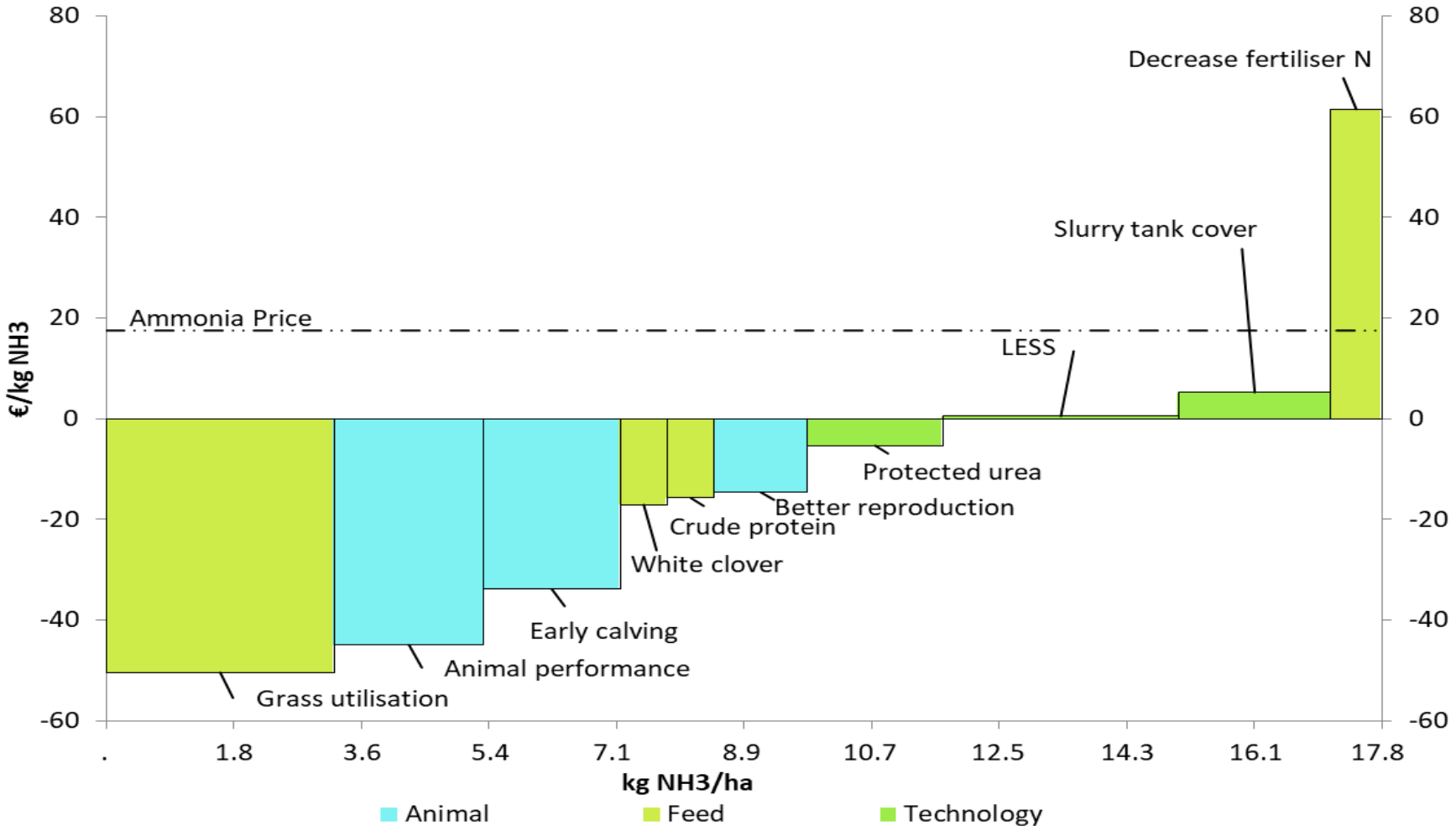

Figure 2b. Ammonia marginal abatement curve for the middle third of Irish dairy farms in terms of economic performance. Abatement potentials correspond to the annual average for the period 2021-2030. Colours indicate the type of mitigation measure. The dashed line represents the shadow price of NH_3.

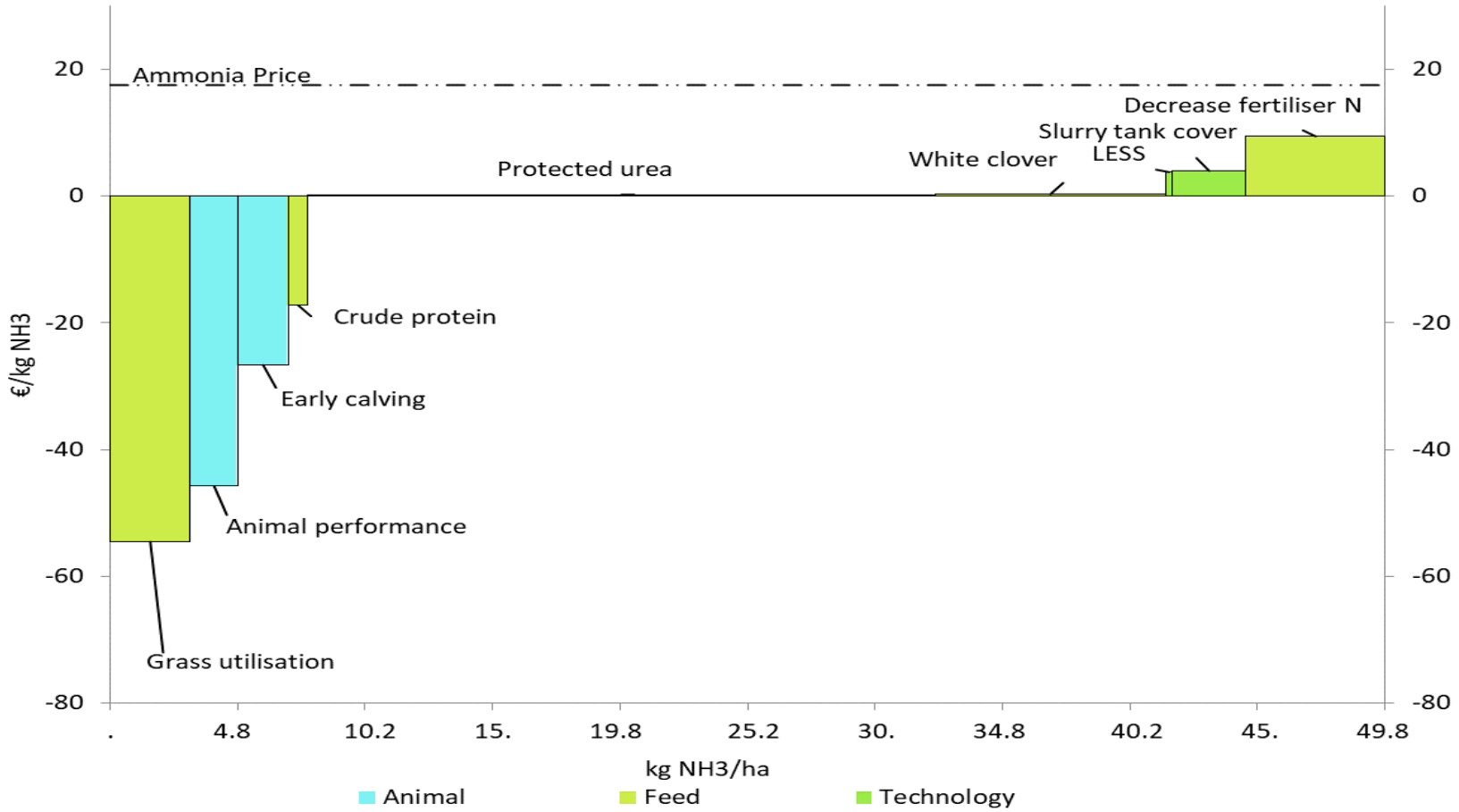

Figure 2c. Ammonia marginal abatement cost curve for the top third of Irish dairy farms in terms of economic performance. Abatement potentials correspond to the annual average for the period 2021-2030. Colours indicate the type of mitigation measure. The dashed line represents the shadow price of NH_3.