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Achieving cleaner growth in agriculture: Establishing feasible mitigation through a bottom-up approach.

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ABSTRACT

Achieving greenhouse gas emission reductions to meet the 1.5 °C target by 2050 is particularly challenging for the agricultural sector. Cleaner Growth Mitigation Measures (CG-MM) are practices and technologies which balance food production with greenhouse gas abatement and are also identified as being economically acceptable. This paper explores a large number of CG-MMs to assess their feasibility using a novel participatory filtering process. Each measure is explored through a series of mapping exercises with supply chain actors to identify the impact on greenhouse gases and their applicability to different farming systems. These are then refined in a series of farmer workshops to identify which measures were considered feasible. Results show that acceptance of CG-MMs by the industry and the farmers themselves is limited. A pessimistic estimate of 50–60% of potential abatement could be lost due to lack of acceptance of currently available CG-MMs within farming. This impacts expectations on decarbonisation trajectories for the agricultural sector to reach net zero by 2050. This also argues for targeted approaches in order to capture some of the lost abatement.

1. Introduction

A number of countries have committed to limit temperatures to a 1.5 °C rise above pre-industrial levels for the 2050–2070 period (UNFCCC, 2015). This requires decarbonisation of all industries and the agricultural sector has only shown limited progress towards these targets (Climate Change Committee, 2022). Emissions from the agriculture, forestry and land use (AFOLU) sector were estimated to be 22% of net anthropogenic GHG emissions in 2019 (IPCC, 2023). Achieving reduced greenhouse gas emissions whilst sustaining food production for a growing population has proven to be a pertinent challenge, for instance Frank et al. (2019) identified sectoral and structural changes needed for the agricultural sector to meet the 1.5 °C target by 2050.

Cleaner growth is part of a policy lexicon which refers to measures such as new technologies and practices that can be adopted to enhance natural capital whilst maintaining or increasing productivity (Department for BusinessEnergy and Industrial Strategy, 2017). The Marginal Abatement Cost Curve (MACC) codifies these measures as the cost of abatement against the magnitude of abatement. In theory, adoption of cleaner growth mitigation measures (CG-MM) would mediate the desire for realising reduced emissions and, in many cases, also enable increasing private returns to incentivise uptake (Eory et al., 2018; Tang and Ma, 2022). However, farming is a fragmented sector with multiple decision-makers that operate under a series of heterogeneous constraints. This will limit adoption of seemingly cost-effective mitigation measures (Yang et al., 2017; Tang et al., 2020; Huber et al., 2023).

Whilst information on the cost-effectiveness of CG-MMs is already available for policy makers through MACCs (Jiang et al., 2020), there is a distinct lack of evidence on how the feasibility of these options are perceived by agricultural stakeholders. Huang et al. (2016) argued that lack of information on the response to these technologies leads to potentially wrong policy prescriptions.

This paper fills the information gap by exploring industry willingness to adopt a suite of CG-MMs. A number of countries are reframing their agricultural policies in light of their 'Green Deal' strategies and establishing policies to meet net zero from food production (EC, 2020; House of Lords Library, 2024; Lee and Woo, 2020). Exploring cleaner growth mitigation methods and their feasibility as perceived by industry offers

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an approach to setting realistic baselines and trajectories for decarbonisation in farming.

2. Literature review

Farming is composed of multiple individual decision makers facing many adoption decisions, and the heterogeneity of these motivations are not only hard to predict, but also relatively under-explored. A parsimonious approach is to simulate the response of individual farmers to GHG incentives in driving adaptation (Barnes et al., 2016; Tang et al., 2018; Tang and Hailu, 2020). However, applied research in this area, is limited and often focuses on a single practice, e.g. no tillage (Alskaf et al., 2020) or a small group of related practices, e.g. nutrient management (Reimer et al., 2012).

The preferences of farmers for feasible measures overlap little with high GHG impact practices. Out of 26 mitigation measures Jones et al. (2013) found only one practice (using grass-legume mixes instead of grass-only pasture) to be highly rated both for GHG impact by experts and for practicality by UK sheep farmers. Similarly, cropping and mixed farmers in Australia were found to have stronger preferences for measures which increase soil carbon content than for practices aiming to increase above-ground biomass (Dumbrell et al., 2016). Scottish dairy farmers ranked grassland measures higher for future adoption, including grass-legume mixtures and using high sugar grass varieties (Glenk et al., 2014).

A growing number of studies focus on the perceived attributes of the practices. The relative importance of the enablers for adoption and barriers differ between practices. Even for practices which are a lot closer to each other the barriers and enablers are slightly different, for example English farmers considered the increased weed burden and more slugs as the main barrier to adopting reduced tillage, while for no tillage three further problems were also raised as important: poor crop establishment, topsoil compaction and lower yield (Alskaf et al., 2020).

Only Feliciano et al. (2014) seem to examine a larger number of practices. They explored 27 practices for their suitability to North-East Scotland. These authors found that financial constraints were mentioned frequently as barriers, particularly for CG-MMs requiring large investment (like precision farming), but a range of different physical constraints were also highlighted, such as the role of weather in reducing nitrogen fertilisation.

This paper adds to the small literature on this topic by seeking to expand the number of mitigation measures explored with farmers using up to date estimates of their feasibility and impact. Moreover, this exercise is replicated across 6 different arable and livestock farm types to reflect the different constraints within systems. The aim is to provide a wider evidence base to establish heterogeneity of response and feasibility for adoption.

3. Methodology

A participatory, multi-step procedure was employed similar to Feliciano et al. (2014) but augmented with visual mapping approaches to allow prioritisation of measures against a range of dimensions. This was repeated across 6 farm types for farmers in England.

3.1. Cost-effective mitigation methods

Agricultural MACCs developed over the last 15 years describe and assess GHG CG-MMs in UK agriculture (Eory et al., 2020), along with policy and industry documents. From these publications a list of 85 GHG mitigation measures were compiled. This initial list was reduced based on three criteria, namely i) confidence in abatement potential, ii) technical feasibility to English agriculture, and iii) risk of negative environmental impacts. This led to a working list of 40 measures (Table 1).

Table 1
List of main cleaner growth measures identified.

ID	Measure
1	Improved crop varieties
2	Use of catch/cover crops
3	Keeping pH at an optimum for plant growth (e.g. liming)
4	Agroforestry
5	Soil-applied bio stimulants
6	Agri voltaic systems
7	Integrated crop health management
8	Integrating grass/herbal leys in arable-only rotations
9	Rotation planning and crop choice for optimum rotational N use efficiency
10	Precision application of N (management zones, in-season adjustment)
11	Active N planning and management to reduce N use and N at risk of loss
12	Use of nitrification and urease inhibitors and controlled release fertilisers
13	Use legumes in crop rotations (biological N fixation)
14	Low emissions slurry spreading
15	Analyse manure prior to application
16	Improving/renovating land drainage (where installed) on mineral soils
17	Reducing soil compaction
18	Take stock off from wet ground
19	Sustainable increase stocking density & grazing management
20	Use grass-legume mixtures in swards (biological N fixation)
21	Integrate higher sugar content grasses
22	AD for animal/crop/food wastes
23	Methanisation, methane capture at (new) slurry pits
24	New improved (low-emission) livestock and poultry housing systems
25	Covering slurry (e.g. oil, plastic, straw, granulates, rigid cover)
26	Breeding for rumen microflora with lower rates of methanogenesis
27	Breeding (non-GM) for lower emission intensity together with improved production indices
28	Genetic selection for reduced methanogenesis
29	GM livestock
30	Animal health and welfare planning
31	High starch; reduced crude protein diet
32	Active diet and feed planning and management
33	Using post-consumer food waste via insects to create high quality livestock feed
34	Dietary supplement with plant extracts/seaweed
35	Dietary supplement - chemical disruptor- 3NOP
36	Biodiverse pasture mixtures for livestock grazing
37	Increased milking frequency
38	Multi use of cows (milk, calves and meat)
39	Paludiculture
40	Shift to low carbon energy in mobile and static machinery

3.2. Identifying feasible mitigation measures

The measures were presented to industry stakeholders in a series of individual interviews. The list of CG-MMs were circulated to a group of 25 stakeholders engaged in the English farming industry. Participants in this process included, amongst others, the Foundation for Common Land, Natural England, the Agricultural Industries Forum, the Green Alliance and Countryside Landowners Association. The interviews were conducted with the purpose of generating comments on the measures and this led to dividing them into a series of more detailed farm management practices (see Appendix 1 and supplementary tables for a full description of measures).

The augmented list was then discussed at a workshop for representatives of all the above stakeholder organisations. The workshop aimed to categorise the measures against their applicability to the main farming systems within England. All CG-MMs were given to the groups and these were mapped in terms of their feasibility of application to each of the 6 farming systems and their expected impact on GHG's. The approach is shown in Fig. 1.

The participants placed each applicable measure on an axis of feasibility for different farm systems (from easy to hard) and GHG impact (from low to high). They were asked to evaluate the expected GHG impact in terms of reduction of emissions at the production unit

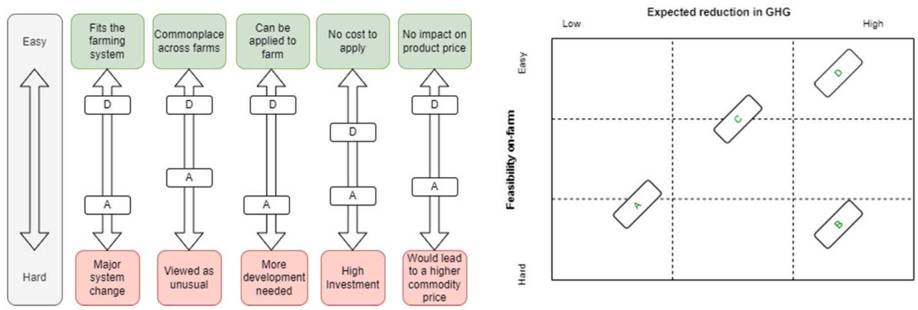

Fig. 1. Participatory grid for CG-MM. The grid was discussed for each farming system and participants were asked to add the mitigation measures in terms of how feasible they are for adoption on that farming system and what their expected greenhouse gas saving would be. For illustration measure A is considered hard to adopt and has low GHG saving overall, whereas measure D is considered easy to implement and has a high impact on GHG saving overall.

level, e.g., from a hectare of land or an animal[1]. To assess feasibility, participants considered five dimensions, based on their judgment and merged these into a single value. These dimensions were a) whether the CG-MM fits to the current farming system or requires major system change, b) whether the CG-MM is commonplace or may be viewed as unusual with peers, c) whether the CG-MM is ready to be implemented by farmers or whether more research and development/technology transfer is needed, d) the magnitude of the financial cost of implementation, such as whether the CG-MM required a high investment, and e) whether it would have no predicted impact on prices or lead to a more expensive product.

The list of feasible measures were then presented at 6 workshops representing English agricultural production, namely arable farming (combinable crops; arable including vegetables); extensive livestock: (lowland extensive; upland cattle and sheep); intensive livestock (cattle and sheep; dairying). The farmers in each workshop were presented with the list of all CG-MMs from the MACC as well as the refined measures identified as feasible from the previous exercise and relevant to their farming system. These workshops were structured around participatory group exercises and discussion. This was a group exercise in which farmers queried specific measures and they discussed what this would mean for their farms in practice. As a group they ranked these measures in terms of their suitability to their enterprise type, ranking measures from the most feasible to those which would be hard to implement. In total 99 farmers attended the workshops.

4. Key results and discussion

4.1. Feasibility mapping by supply chain and NGO representatives

A set of participatory grids were produced with stakeholders for each of the six farming types. Those measures which were considered to have a high impact are discussed below. Figs. 2–5 show the result of the mapping by these representatives.

Arable Farms: The CG-MMs considered most feasible and with the highest GHG impact were around measures which improve soil health (*2. Use of catch/cover crops; 3. Keeping pH at an optimum for plant growth)*. Those considered with a high GHG impact but with medium feasibility were such things as arable reversion, e.g. of arable low input grassland or woodland (*8c*), and implementation of controlled traffic farming (*17b*). Considered less feasible were approaches which moved away from specialisation (*8b*) and integrating grass leys into arable only rotations (*8*) and these needed more demonstration and working case studies to provide confidence in application. Forestry and woodland/trees were also considered to have a high GHG impact but ranged in feasibility ranking ostensibly due to the need for investment (*4-4d: Agroforestry, increasing tree cover on the farm*). This raised discussion of potential fiscal incentives to convert to wood cover, such as tax breaks available for carbon storage (Westaway et al., 2023) The least favourable measure seemed to be around intercropping (*2b. Targeted planning and use of relay/alley intercropping to deliver key farm and on-farm benefits*). Issues around securing quality of harvest were discussed with respect to this measure and the requirement for new machinery which allows value crops to be separated at harvest (Mamine and Farès, 2020).

Extensive cattle and sheep: This is a low-income cohort operating on land which has limited production options (Barnes et al., 2023). For these farming systems it was felt there was little flexibility to adapt, predominantly due to economic fragility and limited production possibilities Therefore, capacity to change may be limited and this is reflected in the small number of CG-MMs that were considered feasible. These were focused on improved grazing management (*18. Taking stock of wet ground*) and recognising the high nature value of these systems *(10c. Identifying less productive land and using innovatively to deliver ecosystem services*). Moreover, this group ranked woodland options more favourably than other farm types (*4. Agroforestry; 4c Increased hedge length; hedge management*). The stakeholders discussed potential support towards capital costs for land use change to address the investment needed to encourage system change. Also, there was a need for more research into farm-specific and appropriate implementation to instil confidence in the measure.

Intensive cattle and sheep: For this sector the most feasible measures with high expected GHG impact were those aimed at better soil health *(3. Keeping pH at an optimum; 17. Reducing soil compaction*). Considered least feasible were anaerobic digestion (*22. AD for animal/crop/food wastes),* principally due to current technical and cost barriers for this sector, as well the viability of ensuring throughput, which has been highlighted in other studies (Ackrill and Abdo, 2020). Whilst considered to have a high impact on emission sequestration, increasing tree cover on farm were also considered least feasible, principally due to the opportunity costs from establishment (*4b. Increased woodland or tree crop coverage on farm*). Moreover, more advanced breeding approaches (*26. Breeding for rumen microflora with lower rates of methanogenesis*) were highlighted due to their cost-effectiveness within the beef sector (MacLeod et al., 2019).

Intensive dairy: Most feasible actions revolved around soil management (*3c. Adopting long-term practices to increase soil organic matter*), as well as grass mixtures for productivity (*21. Integrate higher sugar content grasses*). Of medium feasibility were a tranche of measures for managing grazing land (*18. taking stock off wet ground; 17. reducing soil compaction*) and finding alternative uses for some land (*10c. Identifying less productive land and using innovatively to deliver ecosystem services)*. Least feasible measures were around moving away from specialised production (*8b. Move away from specialisation towards more multi-functional land use*). For this sector, which is highly productive, wider institutional changes may need to occur to enable uptake of measures. Irwin et al. (2023) found

[1] The dimension was specified to avoid confusion with considering the total GHG impact in England, which would have implicitly included assumptions on how widely the measure is applicable and how widespread its uptake would be.

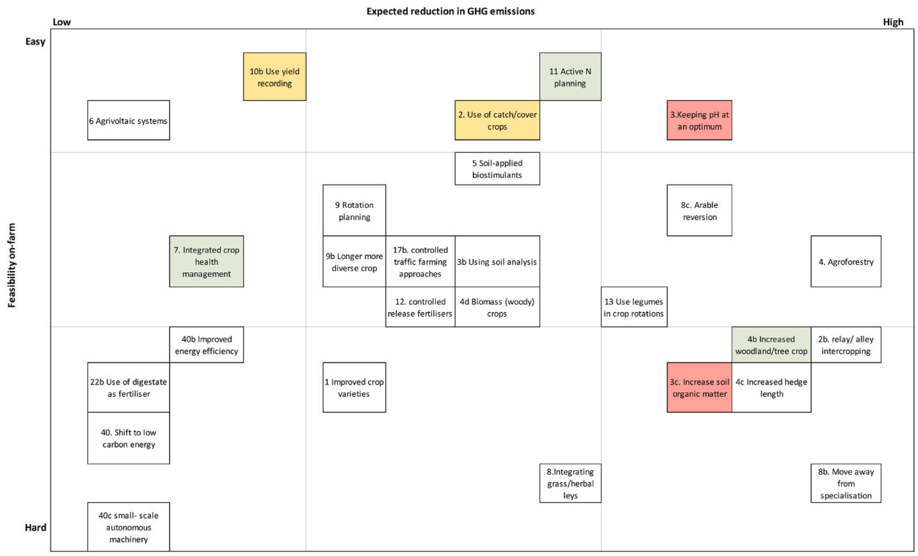

Fig. 2. CG-MMs for the arable sectors mapped by industry and NGO stakeholders and ranked by farmers. This shows the mapping of the mitigation measures considered applicable to cropping systems and further identified by farmers as easy to implement (green), medium feasibility (amber), hard feasibility (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

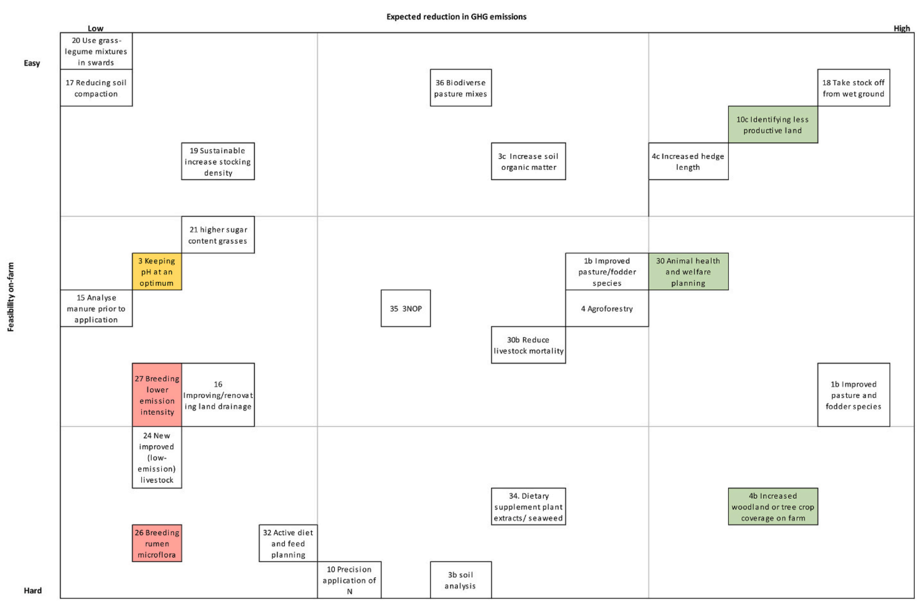

Fig. 3. CG-MMs for the extensive beef and sheep farms mapped by industry and NGO stakeholders and ranked by farmers.

that advisory support and tax-based incentives in Irish dairy farming helped to increase the feasibility of some of these wider mitigation measures.

4.2. Practicality mapping by farmers

The CG-MMs ranked by the farmers are presented against their cost of abatement and expected GHG saving in £(t CO_2e)$^{-1}$. These are shown as bubble plots with the size of the bubble representing the magnitude of abatement from their adoption on farm. The x-axis shows the group ranking score from farmers in terms of their practical feasibility, and the y-axis shows their overall cost of abatement.

Arable farms are shown in Fig. 6a and b. The most feasible measures tended to coalesce around nitrogen planning, precision farming methods and crop health management. A number of farmers had adopted nitrogen management as a way to manage costs on the farm but admitted these were not operated optimally due to lack of information on weather and, in some cases, lack of site-specific advice. Keeping soil health related measures, such as catch and cover crops as well as maintaining pH at an optimum were considered less practicable to implement by the group. Notably these measures had marginally different rankings in terms of their practical application between the two farm types. Soil/land suitability mapping to define management/cropping choices was seen as the most feasible with combinable cropping farmers who argued that most of this is already in place and reflected good practice. Vanino et al. (2023) and Daxini et al. (2019) identified a range of system barriers around infrastructure and knowledge as the main reasons for non-adoption of soil improving approaches.

Farmers considered increasing tree cover on the farm as a long-term approach beyond hedgerow planting and concerns were raised around arable land being taken out of production as well as the relatively long payback time needed. They raised concerns towards land tenancy

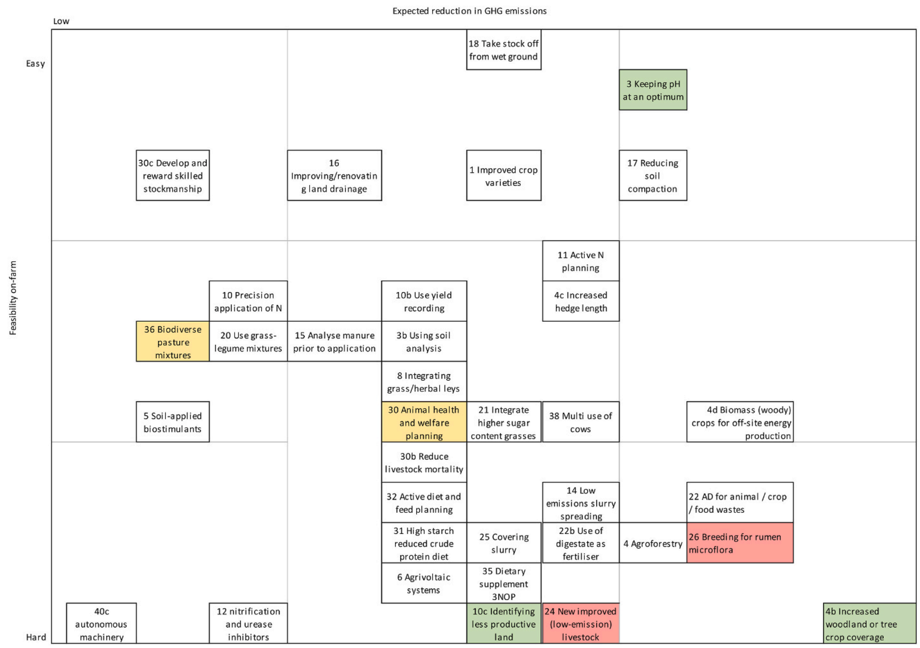

Fig. 4. CG-MMs for intensive beef and sheep mapped by industry and NGO stakeholders and ranked by farmers.

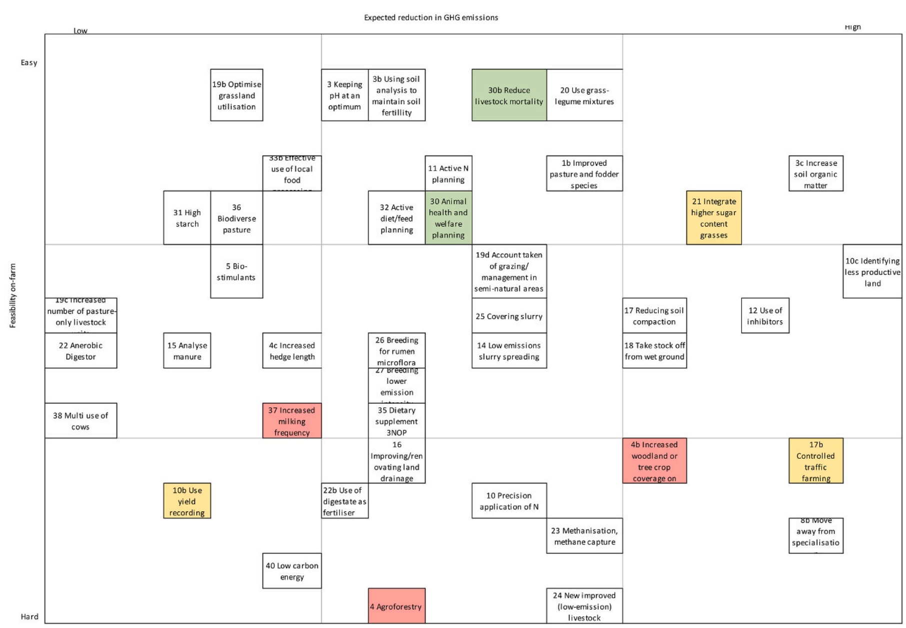

Fig. 5. CG-MMs for the intensive dairy sector mapped by industry and NGO stakeholders and ranked by farmers.

constraints. Felton et al. (2023) found similar concerns in limiting farmer uptake in Southern England and argued for the need to establish alternative markets for woodland production.

Overall, what is noticeable is the mixture of those measures that are considered cost-effective but are also seen as least feasible for the farmers. There also seems to be no clear division between measures which incur smaller compared to larger system changes for feasible adoption on the farm. For the arable sector the less feasible measures were around soil management, and these require farmers to change current practices which incurs risk and costs in changing management planning (Dunn et al., 2016). Reimer et al. (2012) found that the key driver in the adoption of cover crops is farmer interest in improving soil health and fertility, as well as the compatibility of cover crops with current systems of production. This highlights the information gaps raised by these farms to understand the impact on system change and decision-making as a means to adopt these practices.

Extensive upland livestock farms only considered two measures to be feasible, and this potentially relates to the constraints on upland systems to adapt. These are shown in Fig. 7 with the less-intensive lowland systems. There is some commonality in the measures chosen but these are ranked differently by farm type, reflecting the constraints of these systems. Improved grazing, through biodiverse pastures, were favoured by the lowland group. This is considered more feasible as the potential to manage a wider range of grass inputs is greater than for upland contexts.

This also explains why precision farming approaches are more feasible, as a means to manage land under agri-environmental agreements but also to maximise productivity of grass inputs (Barnes et al., 2019). Upland farmers considered agroforestry, in terms of increased

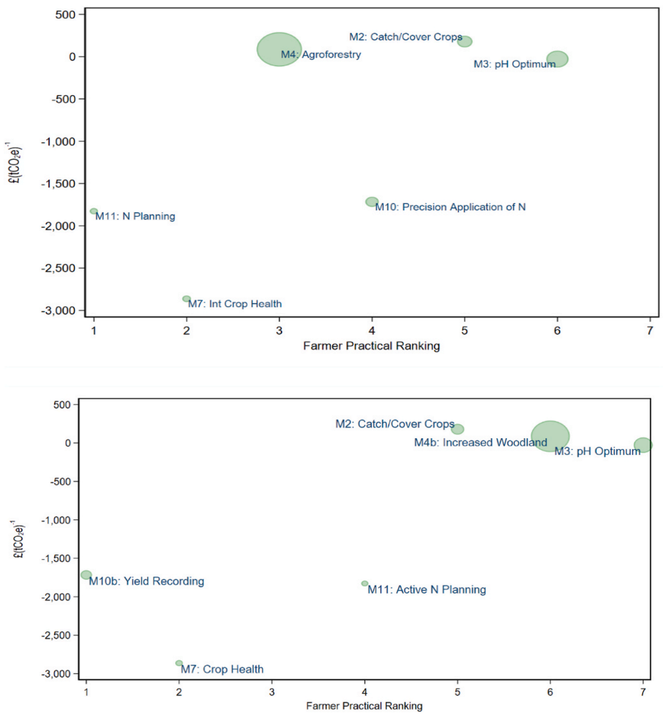

Fig. 6. Arable Farmer ranking of practical CG-MM, cost of abatement and size of abatement (in £ (t $CO_2e)^{-1}$)) against farmer feasibility ranking, where 1 is considered the most practical and 7 the least practical. a) Arable farms with vegetables and b) Combinable Crops.

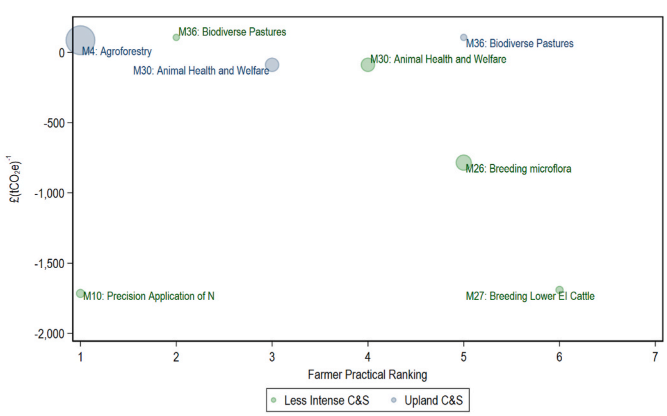

Fig. 7. Extensive livestock farmer ranking of practical CG-MM, cost of abatement and size of abatement (in £(t $CO_2e)^{-1}$)) against farmer feasibility ranking, where 1 is considered the most practical and 7 the least practical.

tree cover, the most feasible. Whilst this may reflect the capacity of land to carry more woodland in the uplands it may also reflect the low level of economic return from upland farming identified by Hardaker (2018). Finally, all farmers ranked animal health and welfare as moderately feasible. In both workshops farmers claimed they were consistently aware of financial issues in managing health and this is similar to the findings of Charlier et al. (2020). The lowland group identified this as linked to improved grazing, e.g. for the reduction gastrointestinal worms or liver fluke. This may also relate to this group's higher ranking for more biodiverse pastures to prevent increased severity of some of these diseases.

The most practical measure considered by intensive beef and sheep farmers (see Fig. 8) was precision application of nitrogen. These farmers explained that this was already being applied under some agri-environmental schemes and areas could be set-aside on farm if they

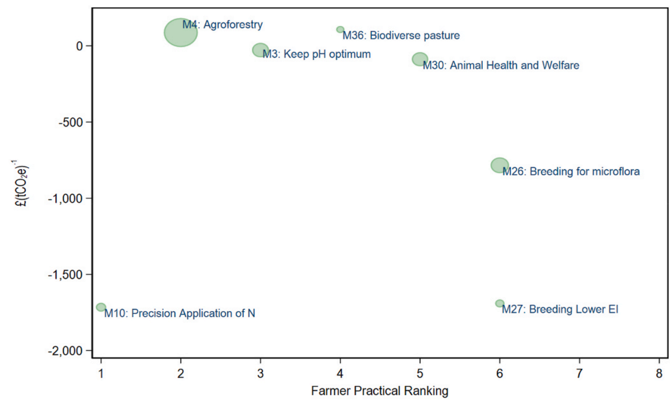

Fig. 8. Intensive beef and sheep farmer ranking of practical CG-MM, cost of abatement and size of abatement (in £(t $CO_2e)^{-1}$)) against farmer feasibility ranking, where 1 is considered the most practical and 8 the least practical.

were given more advice for management of this land. These strategies mitigate environmental risk and may reflect more intensive farmers becoming aware of potential tightening of environmental regulations (Tullo et al., 2019).

The thoughts of the workshop were that increasing tree cover on farm would be good for livestock in terms of shade and potential fuel production. According to the MACC this incurs large establishment costs but the benefits were perceived to outweigh the costs. Farmers discussed the need to sequester emissions to reduce the whole farm carbon footprint as demanded by supply chains. Improved grazing through biodiverse pastures were also favoured, much as they were for the less intensive lowland group.

The farmers also saw improving soil health as feasible and something that farmers should be doing. However, there was limited recorded practice of this in the group and they argued that this measure would require further advice to livestock farmers in how to optimise soil health.

The cattle and sheep sectors viewed the adoption of low-emission breeds as the least feasible option, despite their potential to reduce emissions (Costa Jr et al., 2022). These would require minimal system change but this may reflect a reluctance to adopt perceived less productive animals (Harrison et al., 2016). Conversely, these sectors saw agroforestry as feasible for their land. Small scale woodlands may be more acceptable as studies focused on these farming systems have related to wider objectives stated by farmers, such as biodiversity conservation, landscape improvement and shelter for livestock.

Converse to beef and sheep farmers, the dairy farmers ranked animal health and welfare planning as the most feasible CG-MM (see Fig. 9).

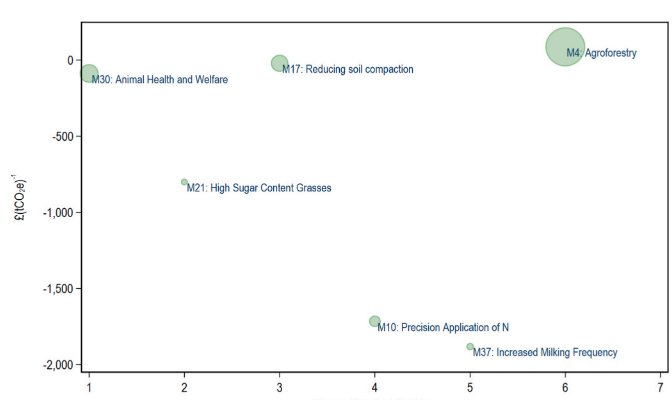

Fig. 9. Intensive dairy farms farmer ranking of practical CG-MM, cost of abatement and size of abatement (in £(t $CO_2e)^{-1}$)) against farmer feasibility ranking, where 1 is considered the most practical and 7 the least practical.

However, this group do have relatively high levels of written animal health plans already (Defra, 2023). This may also be a requirement from milk buyers and a large proportion of those who attended the workshop already had plans in place. High sugar content grasses were also being explored by the group and considered feasible through their reseeding regimes. Similarly, reducing soil compaction was also considered feasible. De Boer et al. (2020) outline a number of approaches to both lift and aerate the soil, and several members of the group had employed these.

Considered least feasible by dairy farmers, in contrast to intensive lowland farmers, were agroforestry measures. This cohort raised an issue over in-field trees blocking farm drains and the need to take into consideration where trees should best be planted. In some cases, increased tree cover was felt to be unfeasible due to local planning issues and restrictions on the farm tenancy. Hence, they argued, any scheme encouraging this would have to be flexibly implemented at a farm level. The lack of flexibility in planting decisions and land use is a common issue raised by farmers with regards to farm woodland expansion (Irwin et al., 2022).

5. Further discussion

Identifying mitigation measures in the MACC provides an estimate of theoretical abatement potential. Table 2 shows the potential abatement of MACC measures that could be adopted at farm level. These are aggregated for those measures which would be applicable to each farm type at an assumed 80% uptake. The figures also assume additivity of the impact of the measures and, consequently, represents an upper limit for savings that could be achieved using cleaner growth measures. This is compared with savings from the technologies and practices that were ranked as either medium or highly feasible by the farmers and shows that only 40–50% of the potential abatement could be achieved through voluntary adoption of these measures.

5.1. Implications for setting decarbonisation pathways

In the wake of the Paris Agreement and successive commitments from UNFCC COP (IPCC, 2022) Governmental decision makers are increasing their ambitions to meet net zero emissions and decarbonise economic sectors. Decarbonising agricultural production is complicated by the multiple uses and demands for land. Gil et al. (2019) examined three strata of decision making, namely globally, regionally and nationally, to evolve emissions intensity in agriculture and illustrated the need for cross-scale thinking to reduce emissions from food. However, sub-nationally there is also significant fragmentation. This paper has shown there are differences in the ability of farms to adopt measures to decarbonise but also differences in perception between those in the supply chain and producers over what is feasible.

Regional farming production is a composite of differing institutional legacies, land ownership, supply chain requirements and artifacts of advisory provision that may enforce barriers to meeting nationally determined commitments. This means that measures which are considered to be economically feasible do not pre-empt adoption. As a consequence, this paper indicates that optimistic adoption scenarios within decarbonisation trajectories leads to high expectations on progress towards net zero targets. This in turn would result in less effective policy interventions, which may be misdirected or targeted at the wrong communities.

Table 2
Summary of theoretical mitigation potential. This is the sum abatement from measures at 80% adoption, assuming additive savings, and compares with those considered either highly or medium feasible for adoption on the farms.

	Potential abatement $ktCO_2e^{-1}$(2050)	Ranked feasible by farmers $ktCO_2e^{-1}$(2050)	% Abatement
Arable	4,267	2,184	51%
Livestock	10,997	4,398	40%

Moreover, a Just Transition is now embedded within climate policies, for instance the European Green Deal (European Commission, 2019), and requires that communities negatively affected by climate policies are supported in the transition. Murphy et al. (2022) examined Irish Beef and Dairy farmers, following protests towards measures to address livestock farmer's emissions. They argued for a greater recognition within this transition of the impact of climate actions to build legitimacy and trust in the process. This implies, at least, community engagement to consider the implications of decarbonising strategies. Understanding the barriers and constraints within the industry will help to moderate these trajectories and help establish more feasible baseline projections for decarbonisation. Maraseni et al. (2021) modelled a regional approach to adoption within the 'Coleambally' catchment in Australia, finding that emissions could be reduced by 50% without compromising food security. Hence, bottom-up studies which explore these measures at a farm system or regional level would seem critical to establishing a realistic baseline.

The practices and technologies around mitigation will change as technology progresses and, we would assume, their attractiveness would also change over time. Table 2 may be seen as a pessimistic assessment of carbon abatement, as cost-effectiveness of measures will improve. A significant uplift has occurred in research and development and migration of technologies from other sectors to raise sustainable agricultural production. This may make adoption more cost-effective in the future and, hence, encourage farmers to reconsider what is feasible. However, there may be long lags in producing workable technology that fit to local farming systems, as is the case for automated technologies, or which meets regulatory approval, as is the case with some feed additives. This raises questions on the type of cleaner growth measures that are being targetted for support and whether there are any common characteristics that make them unattractive, or whether there are facets of farming communities that prove particularly resistant to their adoption, e.g. (Barnes et al., 2022).

5.2. Implications for agricultural support policy

The question of how much of the predicted loss in abatement from current cleaner growth measures could be averted through intervention measures is critical to agricultural and land use policies, both in terms of meeting international commitments but also to ensure cost-effective policy prescriptions. Agricultural support policies tend to rely on a voluntary approach to adoption of environmental measures. For example, the European Commission incentivises voluntary adoption of measures within its Common Agricultural Policy (European Commission, 2020).

Guerrero (2021) in a review of six country's policies towards agri-environmental schemes (Argentina, Australia, Estonia, Finland, Korea, and Portugal) argued that more targeting is required to ensure cost-effectiveness in implementation. Laborde et al. (2021) also found that agricultural subsidies have contributed to an increase in global greenhouse gas emissions and these authors favour the targeting of more punitive measures, such as greenhouse gas taxes. Globally, a range of interventions have been applied or proposed for farming to directly limit GHGs, such as government land buy-out schemes (Boezeman et al., 2023), modifying insurance instruments to induce adaptation to climate change (Jørgensen et al., 2020), or direct producer levies on livestock methane in New Zealand (Leining et al., 2020). The current outlook for meeting net zero, as shown in Table 2 for livestock and cropping sectors, may require these more restrictive interventions if rapid decarbonisation is needed in the agriculture sector. This paper provides some support for these interventions and, at least, argues for increased engagement in these practices through policy support rather than a voluntary approach. Cleaner growth measures are selected on their ability to both maintain or improve food production. These 'win-win' measures and their adoption support the dual goals of reducing GHGs whilst also preserving or improving food security. Hence, more restrictive government interventions for the promotion of CG-MMs should not have adverse impacts on the supply of food.

The scope of this paper is on interventions for food production. It is notable that a growing literature has argued for policy on food consumption. Bajželj et al. (2014) identified the large abatement potential in demand-side mitigation options through reducing waste and changing diets. Demand led interventions may set market signals for producers, for instance Funke et al. (2022) argued for intervention in meat pricing as a means to reduce and target consumption. Whilst artificially changing prices may change signals to reduce production, optimal price setting to meet multiple targets is complex. Smith et al. (2013) supported the need for demand-led measures to cut carbon emissions but also pointed out the lags in effectiveness of this approach and argued that supply-side measures, such as those presented here, allow a reduction in emissions whilst maintaining food production.

6. Conclusions

This paper has extended the consideration of mitigation measures to a range of farming systems. These measures are aligned around the concept of cleaner growth which both balance food production with the mitigation of emissions. The study developed a novel and extensive filtering process to assess a wide range of measures highlighted in the MACC. This also allows an assessment of the potential for lost carbon abatement from technologies that are already available, seen as cost-effective and considered able to fit within current farming systems.

Marginal Abatement Cost Curves is a well accepted tool, which offer parsimony to policy makers for directing effort but there are contextual and regional drivers which will mediate projected savings. This argues for consideration of the nuances of farms and farm systems in order to inform decarbonisation trajectories. Failing to do so would lead to over ambitious expectations on meeting net zero, ignore potential opportunities or misdirect funding that could limit progress towards these targets.

It is further argued that current agricultural support policies, offered through Green Deals, may not go far enough to encourage adoption of all measures that could be applied to these farming systems. Hence, this may require either higher payment rates to incentivise adoption, or targeted approaches which encourage adoption within particular farming systems or regions. Conversely, more punitive measures which penalise non-adoption might be considered. Within the farmer and industry workshops presented here, barriers were raised as not being just economic but also include lack of knowledge around the measures and concern over how the measures fit the system, as well as institutional issues of land tenancy and ownership, especially for longer term measures such as farm woodland.

Finally, as Governments are setting out their plans for future agricultural support which embed climate abatement, the more radical interventions suggested here would lead to structural changes. Accordingly, this paper argues for a Just Transition approach and the process outlined here encourages engagement with affected communities. This would lead to clearer communication between policy and those affected, whilst also ensuring greater legitimacy of sectoral decarbonisation plans and realistic net zero pathways.

CRediT authorship contribution statement

Andrew P. Barnes: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Elizabeth Stockdale:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Lisa Norton:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Vera Eory:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Michael Macleod:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gwen Buys:** Writing – original draft, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

A link to figshare has been added to the manuscript

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142287.

Appendix 1. List of Augmented measures

ID	Measure
1	Improved crop varieties
1b	Improved pasture and fodder species
2	Use of catch/cover crops
2b	Targeted planning and use of relay/alley intercropping etc to deliver key farm and on-farm benefits
3	Keeping pH at an optimum for plant growth (e.g. liming)
3b	Using soil analysis to maintain soil fertility
3c	Adopting long-term practices to increase soil organic matter
4	Agroforestry
4b	Increased woodland or tree crop coverage on farm
4c	Increased hedge length; hedge management to increase C sequestration

(continued on next page)

(*continued*)

ID	Measure
4d	Biomass (woody) crops for off-site energy production
5	Soil-applied bio stimulants
6	Agri voltaic systems
7	Integrated crop health management
8	Integrating grass/herbal leys in arable-only rotations
8b	Move away from specialisation - more multi-functional land use, multi-operator mixed systems
8c	Arable reversion
9	Rotation planning and crop choice for optimum rotational N use efficiency
9b	Longer more diverse crop rotations (time) and cropping patterns (space)
10	Precision application of N (management zones, in-season adjustment)
10b	Use yield recording to identify differently performing areas and target management
10c	Identifying less productive land and using innovatively to deliver ecosystem services (may not just be GHG mitigation)
10d	Improvements in precision/flexibility of current machinery (reducing numbers of passes)
11	Active N planning and management to reduce N use and N at risk of loss
12	Use of nitrification and urease inhibitors and controlled release fertilisers
13	Use legumes in crop rotations (biological N fixation)
14	Low emissions slurry spreading
15	Analyse manure prior to application
16	Improving/renovating land drainage (where installed) on mineral soils
17	Reducing soil compaction
17b	Implementation of controlled traffic farming approaches
18	Take stock off from wet ground
19	Sustainable increase stocking density & grazing management
19b	Optimise grassland utilisation - effective planning and management
19c	Increased number of pasture-only livestock units with extensive grazing but high overall grassland utilisation
19d	Careful account taken of grazing/management in semi-natural areas
20	Use grass-legume mixtures in swards (biological N fixation)
21	Integrate higher sugar content grasses
22	AD for animal/crop/food wastes
22b	Use of digestate as fertiliser - low-emission application, replacing fertiliser N
23	Methanisation, methane capture at (new) slurry pits
24	New improved (low-emission) livestock and poultry housing systems
25	Covering slurry (e.g. oil, plastic, straw, granulates, rigid cover)
26	Breeding for rumen microflora with lower rates of methanogenesis
27	Breeding (non-GM) for lower emission intensity together with improved production indices
28	Genetic selection for reduced methanogenesis
29	GM livestock
30	Animal health and welfare planning
30b	Reduce livestock mortality
30c	Develop and reward skilled stockmanship
31	High starch; reduced crude protein diet
32	Active diet and feed planning and management
33	Using post-consumer food waste via insects to create high quality livestock feed
33b	Effective use of local food processing wastes on-farm
33c	Improved use of human wastes - domestic and industrial (closing the loop)
34	Dietary supplement with plant extracts/seaweed
35	Dietary supplement - chemical disruptor- 3NOP
36	Biodiverse pasture mixtures for livestock grazing
37	Increased milking frequency
38	Multi use of cows (milk, calves and meat)
39	Paludiculture
40	Shift to low carbon energy in mobile and static machinery
40b	Improved energy efficiency/renewable energy for grain drying
40c	Development and deployment of small- scale autonomous machinery

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