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Assessing the effectiveness, practicality and cost effectiveness of mitigation measures to reduce greenhouse gas emissions from intensively cultivated peatlands

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ABSTRACT

Peatlands drained for agriculture are among the most intensive sources of greenhouse gas (GHG) emissions from the land-use sector. Policy decisions on the most effective strategies to reduce GHG emissions in line with Paris Agreement goals, alongside strategies that can halt any ongoing soil and biodiversity losses, are hindered by a lack of understanding on how proposed mitigation measures are likely to be received by the farming sector. Research has identified effective GHG reduction measures, but successful on-farm adoption of these measures is contingent upon farmer perceptions of the relative practicality of implementing the measures, and the economic impact that adoption will have on the farm business. In this study, Best–Worst Scaling, a discrete choice survey method, was utilised to elicit expert (climate change, policy and biodiversity) and farmer opinion on the relative effectiveness, practicality and level of economic cost of mitigation measures that can reduce GHG emissions at the farm level. The method enabled individual mitigation measures to be ranked by effectiveness (expert opinion), practicality and economic cost (farmer opinions). There were no measures ranked as both effective and practical, or effective with low cost, but there were measures ranked by farmers as practical and low cost to implement. These included: more effective nutrient management, reduced or no tillage, the installation of buffer zones, increased fossil fuel efficiency and the optimisation of irrigation systems. The strong divergence of 'effective' measures on the one hand, and 'practical' and 'economic' measures on the other, highlights the major challenges involved in reducing high GHG emissions from agricultural organic soils. Resolving these challenges will require a combination of financial mechanisms to compensate farmers for higher costs and/or reduced yields, engagement and advice to support farmers in adopting changes in management practice, and agricultural innovation and adaptation to maintain overall food production and economic viability. If these challenges are overcome, more sustainable landscape management on agricultural lowland peat could make significant contributions to achieve national and international climate change targets.

1. Introduction

In their natural state, peatlands continuously sequester CO_2 from the atmosphere (Evans et al., 2017) and are, at least in their early life, significant carbon (C) sinks (Belyea and Clymo, 2001). They provide a diverse range of ecosystem services as part of their natural functioning, including regulating services such as climate regulation via C sequestration and storage, water regulation and water purification (Bonn et al., 2016; Grzybowski and Glińska-Lewczuk, 2020), and they are also important for biodiversity. In general, however, utilising peatlands for direct economic return generally involves drainage practices to allow for their conversion to productive uses such as food and fibre or use of peat as a fuel or growing medium production (Dinesen et al., 2021). These activities all lead to rapid, substantial and ongoing loss of soil organic C, CO_2 emissions and other greenhouse gases (GHGs; notably N_2O from fertilised organic soils), land-subsidence, and to the degradation of other

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ecosystem services (Evans et al., 2019; Page and Baird, 2016; Parish et al., 2008).

Globally the drainage of lowland peat for farming and other provisioning services is estimated to have affected 12 % of global peatlands (Dinesen et al., 2021), transforming them from long-term C sinks into C sources, which have been estimated to contribute between 2 % and 5 % of all anthropogenic GHG emissions (Evans et al., 2019; Joosten, 2009; Leifeld and Menichetti, 2018). In the UK, 53 % of the total peatland GHG emissions are from lowland peatlands drained for agriculture (Brown et al., 2023), despite these areas only occupying 6 % of the total peat area in the UK. In the context of agricultural land, agricultural drained peat has the highest GHG emissions per unit area of any other agricultural land-use in the UK (Evans et al., 2017).

The large-scale drainage of UK lowland peat areas began in the 17th century with the development of engineered drainage systems in Eastern England, most extensively in the Fenlands of East Anglia (Thompson, 1957). Subsequently, peatland drainage has extended to many other areas including the Somerset Levels, Norfolk and Suffolk Broads and the Lancashire Mosslands (Natural England, 2010). Similar large-scale drainage of peatlands for agriculture and forestry has occurred across much of Europe including the Netherlands, Germany and Fennoscandia, as well as in parts of North America and (more recently, but on a very large scale) across Southeast Asia (Page and Baird, 2016).

Drained peatlands will continue to be a hotspot of GHG emissions of global importance unless action is taken (Parish et al., 2008; Tubiello et al., 2016; Wüst-Galley et al., 2020). Agreeing that urgent action is required to reduce GHG emissions globally has led to the development of agreements such as the Paris Agreement (United Nations / Framework Convention on Climate Change, 2015), whilst the Ramsar Convention on Wetlands agreement is more targeted with the aim to protect, sustainably manage and restore, peatlands (Ramsar, 2018).

In just 200 years since the 18th century, the UK has lost 84 % of the fertile peat topsoil in East Anglia, with <1 % of the original 4000 km^2 continuing to support wetland habitat, and the remainder in danger of being lost in just 30–60 years (Adaptation Sub-Committee, 2013; DEFRA, 2018a; Mulholland et al., 2020) Consequently, the UK's first collaborative Peatland Strategy (Bain et al., 2011; DEFRA, 2018a) was developed to capture and embed, for the long term, a shared vision for UK peatlands. This strategy aims to shift the management of drained peatlands under intensive production, to farming practices which deliver wetter ways to farm. In 2020, the UK Department for Environment, Food and Rural Affairs, which has oversight of farming activities in England, established a Lowland Agricultural Peat Task Force with a remit to identify options for better management of lowland peatlands to safeguard productive agriculture while contributing to delivering the government's 2050 Net Zero target.

Increasing pressures to meet existing policy agreements has led to a variety of mitigation measures being identified as potential measures to reduce GHG emissions on agricultural lowland peat, such as; paludiculture, (i.e. wetland-based farming; (Gaudig et al., 2017; Mulholland et al., 2020; Schlattmann and Rode, 2019), higher water table management within existing farming systems (Freeman et al., 2022; Kløve et al., 2017; Rhymes et al., 2022; Taft, 2014), rewetting and peat restoration (Liu et al., 2020; Renou-Wilson et al., 2019) and the use of 'regenerative farming' measures (e.g. reduced tillage, fertiliser management and cover crops; Wen et al., 2021). Despite identified mitigation measures, the evidence base upon which to make strategic management decisions to reduce emissions remains limited (Freeman et al., 2022; Taft, 2014; Taft et al., 2018) because the practicalities and economic impacts of adopting these measures are still unclear.

Furthermore, the adoption of these mitigation measures is contingent upon farmer perceptions of the relative practicality of implementation (Jones et al., 2013; Taft, 2014). If farmers are to adopt mitigation measures it is imperative that they are (i) practical, (ii) economic, (iii) legally compliant, (iv) acceptable to retailers, and (iv) acceptable to the general public. Previous studies on farm-scale adoption of GHG mitigation strategies (Jones et al., 2013; Taft, 2014) found disagreement between what was deemed effective (expert opinion) and what was considered practical (farmer opinion). With this study we used two linked Best-Worst Scaling (BWS) surveys: one to assess practicality and economic cost of different mitigation measures, and the other to assess the efficacy of different mitigation measures. We took this approach to expand from the 2-dimensional (i.e., practicality vs effectiveness) analysis approach used in previous studies (Jones et al., 2013; Taft, 2014) to allow for a multi-dimensional one. This allows for a more holistic understanding of mitigation strategy uptake to aid in new policy decisions that can foster higher mitigation measure and technology adoption.

2. Methodology

2.1. Shortlisting mitigation measures

An initial list of 73 candidate mitigation measures were identified from relevant peer-reviewed papers and grey literature (Table S1). The 73 mitigation measures were reduced to 50 (Table S2) by removing any identified in a previous study as being slightly or not effective (Taft, 2014). The list of mitigation measures was further shortened to a manageable 30 by a panel of 13 scientific experts, identified on the basis of authorship of relevant papers relating to the reduction of GHG emissions from agriculture on lowland peat. The panel was asked to evaluate each measure in terms of its potential to reduce GHG emissions on agricultural lowland peat at the farm level. The classification options were "very effective", "quite effective", "slightly effective", "not effective" or "don't know". Using methodology adapted from previous studies (Jones et al., 2013; Taft, 2014), responses were scored with values of "3", "2", "1", "−1″, and "0" respectively, and summed for each mitigation measure.

The 30 most effective mitigation measures identified by the panel of experts (Table 1) were grouped by the following mitigation types: restoration (two measures); paludiculture (six measures); water management (eight measures); crop management (three measures); nutrient management (four measures); regenerative management (four measures); farm machinery usage (two measures) and miscellaneous (one measures). These mitigation measures were subsequently used to populate the Best Worst Scaling (BWS) surveys.

2.2. Best-Worst scaling

BWS is an extension of the paired comparisons approach; where participants are presented with a predetermined number of choice sets of five candidate items (in this study, these items represent individual mitigation measures) and are asked to choose the two items within each set that they consider the 'best' and 'worst' (Finn and Louviere, 1992).

Best Worst Scaling methods were chosen because they have; 1) a greater discrimination between elements compared to alternative ranking techniques such as the Likert Scale; 2) reduced intellectual burden than ranking multiple elements simultaneously; and 3) provision of more information than other methods when the respondent is indifferent or dislikes both options. These Best Worst Scaling methods have been used previously in agricultural GHG emission mitigation studies in the UK (Glenk et al., 2014; Jones et al., 2013) and Australia (Dumbrell et al., 2016) – with the latter exploring preferences to adoption of carbon farming practices via an online BWS survey.

2.3. Survey designs

Two surveys were developed with targeted questions for either expert respondents, chosen for their expertise in GHG emissions from agricultural lowland peat, or farmer/landowner respondents who farm on all/some peatland soil. Each survey consisted of eighteen choice sets with five mitigation measures within each. Experts (n = 27) were asked

Table 1
Shortlisted mitigation measures used in the expert effectiveness, and farmer practicality and economic best/worst scaling surveys. The scores are based on an effectiveness scale from −1 (not effective) to 3 (very effective).

Number	Mitigation measure	Mitigation type category	Mean Score
1	Fill/block ditches	Water management	2.7
2	Raise average water levels	Water management	2.6
3	Restore cropland to native wetland vegetation	Restoration	2.6
4	Avoid additional draining and cultivation	Water management	2.4
5	Produce food/fodder crops on high water table peatland	Paludiculture	2.4
6	Produce perennial reed grasses for construction material.	Paludiculture	2.4
7	Maintain shallow water table for longer	Water management	2.1
8	Establish rushes, sedges and wetland grasses	Paludiculture	2.1
9	Produce biomass (Sphagnum moss) for restoration or as a raw material	Paludiculture	2.0
10	Combine solar panels with Sphagnum production	Paludiculture	1.8
11	Raise the groundwater table in the non-growing season	Water management	1.8
12	Cultivate cover crops (e.g., rye) in combination with a raised water table	Crop management	1.7
13	Raise water levels during winter when fields are fallow	Water management	1.6
14	Restore/create peatland vegetation	Restoration	1.5
15	Reduce nitrogen fertiliser dose	Nutrient management	1.5
16	Establish infrastructure to support dynamic soil moisture management	Water management	1.5
17	Convert cropland to grassland (e.g. pasture)	Crop management	1.3
18	Increase the use of perennial food crops	Crop management	1.3
19	Improve timing of nitrogen fertiliser application	Nutrient management	1.2
20	Eliminate tillage (i.e. zero-till)	Regenerative management	1.2
21	Install buffer zones	Regenerative management	1.2
22	Produce bio-energy crops such as willow and miscanthus	Paludiculture	1.2
23	Use more fuel-efficient machinery and equipment	Farm machinery usage	1.1
24	Conduct soil and crop nutrient testing and management planning	Nutrient management	1.1
25	Optimise irrigation system efficiency to keep soil moist but not saturated	Water management	1.1
26	Avoid or shorten bare fallow periods	Regenerative management	1.1
27	Minimise farm machinery usage	Farm machinery usage	1.0
28	Reduce tillage	Regenerative management	1.0
29	Increase reliance on nitrogen-fixing crops (legumes)	Nutrient management	1.0
30	Use anaerobic digestion with energy recovery, or bio-fuel production	Miscellaneous	1.0

to indicate which GHG mitigation measures within a choice set they perceived as the "most effective" and "least effective" for reducing emissions. Whilst, farmers and landowners (n = 123), were asked to indicate which mitigation measures they perceived as "most practical" or "least practical" to implement along with which measures had "most economic cost" and "least economic cost "to the business.

Optimum survey designs were developed using Sawtooth SSI Web 7, version 7.0.10 software (Sawtooth Software Inc., Orem, UT, USA), where randomised choice sets based on a 1000 choice set iterations ensured that each mitigation appeared an equal number of times across the eighteen survey choice sets (Sawtooth Software, 2020). This ensures a balanced and efficient design to reduce respondent fatigue.

Multiple variations of the optimal survey design were used in the online survey to vary the position of mitigation measures within each choice set with a combination of measures across respondents to help minimise context bias (Sawtooth Software, 2020; Taft, 2014). An example of a BWS choice set is provided in Fig. 1.

2.4. Data collection

Study protocols were reviewed and approved by the Ethics Committee of Bangor University (Approval number: COESE2020JDA01A) and DEFRA Survey Control. All respondents were informed that data collection was anonymous and that they were free to stop participation at any time. Participants also provided informed consent prior to completing the surveys. Experts with knowledge of GHG mitigation measures were recruited from academia, government and environmental NGOs.

To reduce bias, experts involved in shortlisting were not directly invited to participate in the online survey. Expert surveys were completed online between September and December 2020. Farmers and landowners were recruited through engagement with the National Farmers Union (NFU), who distributed a link to the survey to their members farming on lowland peat soils, and through other stakeholder contact lists. Data were collected between 01 December and 24 December 2020. Demographic data collected from experts included gender, age, and type of organisation and for farmers and landowners, gender, age, enterprise (horticulture, vegetable, fruit, ornamentals, arable and other), farm size, area of peat (ha), farmer peat area (ha) and ownership/tenancy.

2.5. Analysis

2.5.1. Hierarchical bayes multinomial logit and extensions

Mitigation measure effectiveness scores (experts perceptions), practicality and scores (farmer and/or land owner perceptions) were estimated using a choice model based on random utility theory, modelled using multinomial logit (MNL; Sawtooth Software, 2020). This method borrows information across the distribution of responses to stabilise and calculate each respondent's score for each mitigation measure.

Under the logit rule, the probability of choosing the i^{th} item as best (or most important) from a set containing $_i$ through $_j$ items is equal to:

$$P_i = e^{Ui} / \Sigma\, e^{U}_{ij}$$

where e^{Ui} means to take the antilog of the utility for item *i*.

and the probability of choosing the i^{th} item as worst (or least important) is equal to:

$$P_i = e\text{-}^{Ui} / \Sigma\, e\ \text{-}^{U}_{ij}$$

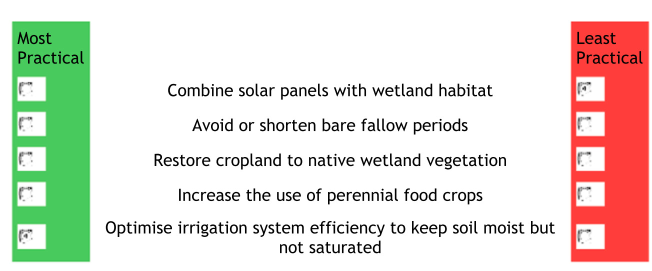

Fig. 1. Example of a 'practicality' Best-Worst Scaling choice set. Respondents were invited to check one, mutually exclusive, radio button in each column, corresponding to their opinion on the 'most practical' and 'least practical' option respectively within each set.

where e^{-U_i} means to take the antilog of negative the utility for item *i*.

For further details of the workings of the multinomial logit model and individual level score estimation see Cross et al. (2012), Finn and Louviere (1992) and Sawtooth Software (2020). The effectiveness, practicality and economic scores were rescaled to sum to 100 across all mitigation measures, placing the scores on a ratio scale and aiding interpretation.

Based on individual scores, individual fit statistics, which are a measure of internal consistency indicating the reliability of a respondent's answers, were calculated with the Sawtooth SSI Web 7, version 7.0.10 software (Sawtooth Software Inc., Orem, UT, USA). Any respondent whose fit statistic was less than 25 % was removed from further analysis as their responses were considered unreliable (2 farmers).

2.5.2. Statistical analysis

Farmer demographic data were used to assess whether the distribution of individual respondent practicality scores differed significantly between subgroups of respondents. Kruskal–Wallis tests with Dunn–Bonferroni post hoc tests (Jones et al., 2013) were conducted to compare the distribution of individual respondent scores between subgroups of interest, for example gender, age and farm type. Epsilon square (ε^2) was used to indicate how strong the demographic groups influence practicality and economic scores. An epsilon square of 0 would mean no differences (and no influence), while one of 1 would indicate a full dependency. (Tomczak and Tomczak, 2014). All statistical tests were performed using SPSS 27 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Survey demographics

Twenty-seven experts (~40 % of those contacted) completed the effectiveness BWS survey (Table 2). The farmer survey consisted of two separate BWS sections, a practicality and an economic section. A total of 143 respondents (22 % of those contacted) completed the practicality section but only 123 of those farmers went on to complete the economic section. This was reduced to 141 and 121 respectively as 2 farmers were removed because their fit statistic was lower than 25 %. Respondents came from different geographic locations (the Fens, Humberhead Levels, the North West, North East and Somerset Levels; Figs. 2 and 3) and demographic backgrounds (Table 3).

3.2. Expert effectiveness scores

The estimated mean expert rescaled scores for the 30 mitigation measures obtained via the hierarchical Bayes estimation described in Section 2.4.1, were ranked on a scale of effectiveness (Fig. 4). The scores were zero-centred so that the y-axis represented the overall mean effectiveness score of the 30 mitigation measures. Measures to the left of the x-axis received below average effectiveness scores and measure to the right of the x-axis achieved above average effectiveness scores.

Table 2
Demographics and area of expertise of expert respondents to the effectiveness BWS survey.

Grouping variable	Category	Number of respondents
Gender	Male	17
	Female	9
	Prefer not to say	1
Age	25–34	4
	35–44	9
	45–55	8
	> 55	6
Area of expertise	Regulatory	3
	Research	17
	NGO	7

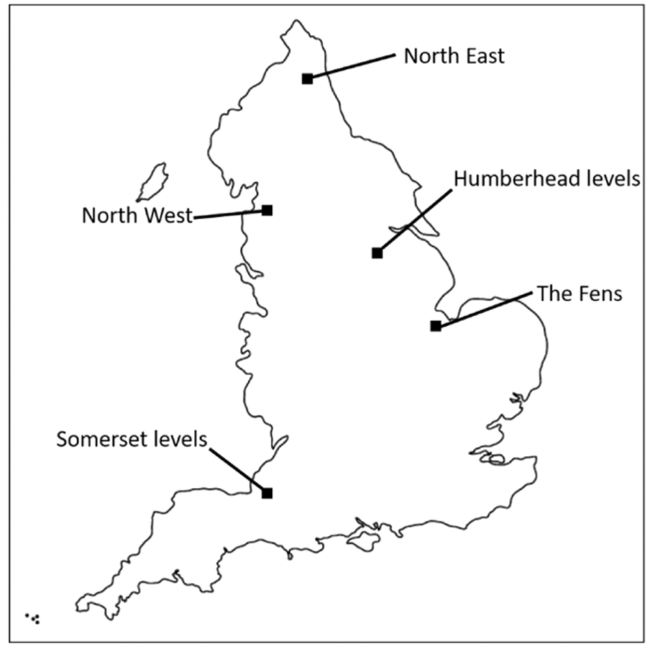

Fig. 2. The geographic distribution and grouping of farmer respondents.

Nine measures received scores that were significantly above the mean (i.e. their confidence intervals (CI) do not overlap the zero-centre; Fig. 4). Mitigation measure 3: Restore cropland to native wetland vegetation, in the restoration category, was deemed the most effective measure for reducing overall GHG emissions, with a score of 6.24 ± 0.29. The second most effective, also in the in the restoration category was mitigation measure 14: Restore/create peatland vegetation with a score of 5.89 ± 0.52. The other effective measures were in the paludiculture category (9: Produce biomass (Sphagnum moss) for restoration or as a raw material, with a score of 3.41 ± 1.25; 8: Establish wetland species such as rushes, sedges and wetland grasses for the production of animal litter, with a score of 3.09 ± 1.16 and 5: Produce food/fodder crops on high water table peatland, with a score of 2.95 ± 1.05); water management (2: Raise average water levels, with a score of 3.45 ± 1.01; 1: Block ditches to raise water levels, with a score of 3.52 ± 0.99 and 16: Establish infrastructure to support dynamic water management, with a score of 1.89 ± 0.99) and crop management categories (12: Cultivate cover crops (e.g., rye) in combination with a raised water table, with a score of 1.23 ± 1.17). The mitigation measure deemed least effective was measure 23: Use more fuel-efficient machinery and equipment (farm machinery usage category), with a score of −3.16 ± 0.12.

The CIs around the mean scores indicate some uncertainty and/or disagreement associated with the effectiveness of the mitigation measures. The CIs were lower in the top and bottom two effective and ineffective mitigation measures indicating a good level of consensus between the experts in determining effectiveness. CIs are higher in the mid-range mitigation measures indication some levels of uncertainty over the effectiveness/ineffectiveness of these measures.

3.3. Farmer practicality scores

The estimated mean rescaled farmer scores for the 30 mitigation measures were ranked on a scale of practicality (Fig. 5). Again, the scores were zero-centred so that the y-axis represents the mean practicality score of the 30. Eleven measures had practicality scores significantly more than the overall mean. Four of the 11 mitigation measures deemed practical to implement are related to nutrient management (24:

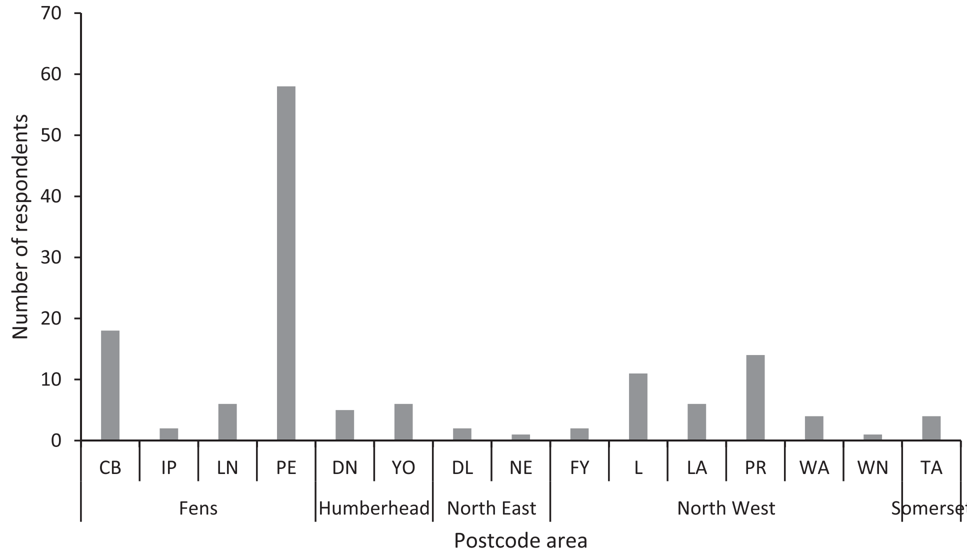

Fig. 3. The geographic distribution of farmer respondents to the practicality and economic BWS surveys.

Table 3
Demographics of farmer respondents to the practicality and economics BWS surveys.

Grouping variable	Category	Number of respondents
Gender	Male	126
	Female	15
	Prefer not to say	2
Age	18–24	1
	25–34	10
	35–44	12
	45–55	36
	>55	81
Enterprise	Horticulture (vegetables)	3
	Other horticulture	3
	Arable	73
	Mixed arable/horticulture	33
	Other	28
Farm Size	<100 ha	30
	100–199 ha	34
	200–499 ha	47
	500 + ha	29
Total peat area	<100 ha	103
	100–199 ha	23
	200–499 ha	10
	500 + ha	5
Farmed peat area	<100 ha	105
	100–199 ha	24
	200–499 ha	9
	500 + ha	5
Average peat depth	0–40 cm	58
	40–60 cm	23
	>60 cm	28
	Unsure	33
Ownership/ tenancy	Majority of land owned	92
	Majority of land tenanted	44
	Majority of land let to external party	1
	Other	2

Conduct soil and crop nutrient testing and management planning, with a score of 4.41 ± 0.39 and 19: Improve timing of nitrogen fertiliser application, with a score of 4.04 ± 0.36 and 15: Reduce nitrogen fertiliser dose, with a score of 3.43 ± 0.38 and 29: Increase reliance on nitrogen-fixing crops (legumes), with a score of 1.85 ± 0.40).

The other practical mitigation measures were in the regenerative management category (21: Install buffer zones, with a score of 3.89 ± 0.36, 28: Reduce tillage, with a score of 3.62 ± 0.40, 20: Eliminate Tillage, with a score of 0.78 ± 0.56 and 26: Avoid or shorten bare fallow periods, with a score of 3.40 ± 0.39); farm machinery usage (27: Minimise avoidable use of farm machinery, with a score of 3.67 ± 0.44 and 23: Use more fuel-efficient machinery and equipment, with a score of 3.46 ± 0.41) and water management (25: Optimise irrigation system efficiency to keep soil moist but not saturated, with a score of 0.62 ± 0.53). The mitigation measure deemed least practical was 9: Produce biomass (Sphagnum moss) for restoration or as a raw material (paludiculture), with a score of −2.64 ± 0.16. The CIs were reasonably consistent across all mean scores and smaller than those associated with the mean expert effectiveness scores indicating a higher level of consensus between the farmers in determining levels of practicality.

3.4. Farmer economic scores

The estimated mean rescaled farmer scores for the 30 mitigation measures were ranked on a scale of the economic cost (does not decipher between implementation costs or economic impact on profits) of implementing GHG mitigation strategies on the farm (Fig. 6). Again, the scores have been zero-centred so that the y-axis represents the mean economic score of the 30.

Eleven measures had economic scores significantly more than the overall mean, meaning they would have the least economic cost to the farm if implemented. The mitigation measure having the least economic cost to the farm was 24: Conduct soil and crop nutrient testing and management planning, with a score of −4.39 ± 0.39. The three other nutrient management measures were also deemed to have low economic cost (19: Improve timing of nitrogen fertiliser application, with a score of 3.89 ± 0.40; 15: Reduce nitrogen fertiliser dose, with a score of 2.48 ± 0.50 and 29: Increase reliance on nitrogen-fixing crops (legumes), with a score of 2.30 ± 0.44). Other categories with mitigation measures having a low economic cost include: farm machinery usage (23: Use more fuel-efficient machinery and equipment, with a score of 4.20 ± 0.40 and 27: Minimise avoidable use of farm machinery, with a score of 4.02 ± 0.41); regenerative management (28: Reduce tillage, with a score of 3.62 ± 0.39; 20: Eliminate tillage (i.e. zero-till), with a score of 1.59 ± 0.57; 21: Install buffer zones between fields and watercourses, and within fields, to catch leached nutrients and soil organic carbon, with a score of 2.66 ± 0.48 and 26: Avoid or shorten bare fallow periods, with a score of 2.76 ± 0.40) and water management (25: Optimise irrigation system efficiency to keep soil moist but not saturated, with a score of 1.01 ± 0.61). The mitigation measure with the lowest mean

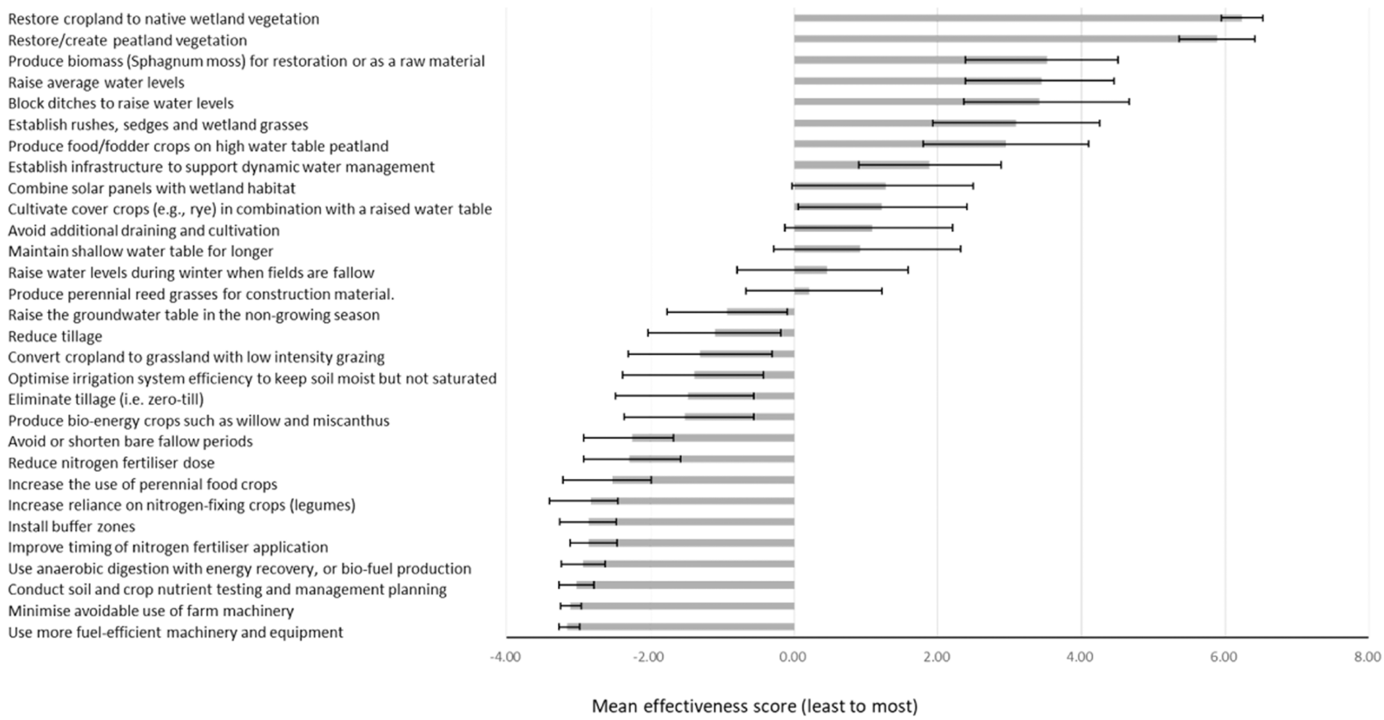

Fig. 4. Rescaled mean estimates of the effectiveness scores across all experts for the 30 shortlisted mitigation measures. The error bars represent 95 % confidence intervals of the mean scores. Values represent n = 27. The scores were rescaled to sum 100 across all the mitigation measures to aid interpretation.

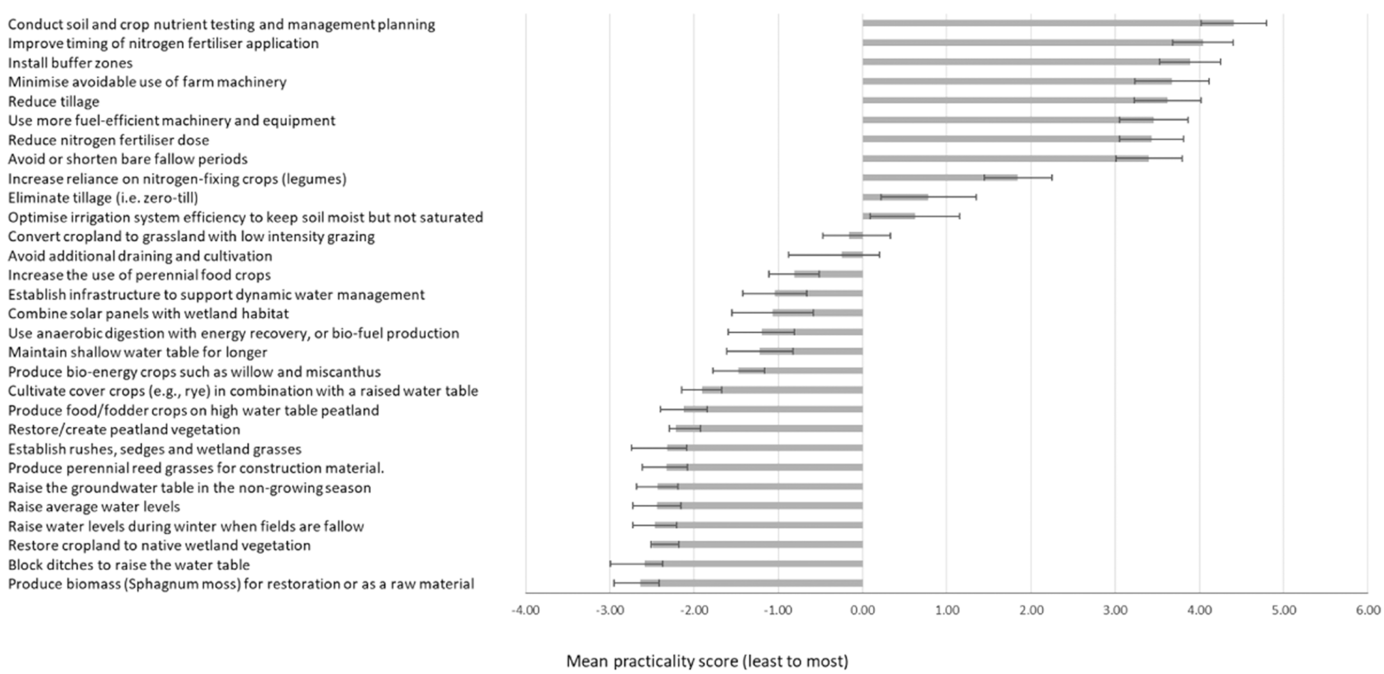

Fig. 5. Rescaled mean estimates of the practicality scores across all farmers for the 26 shortlisted mitigation measures. The error bars represent 95 % confidence intervals of the mean scores. Values represent n = 141. The scores were rescaled to sum 100 across all the mitigation measures to aid interpretation.

score indicating the highest economic cost was 1: Fill/block ditches to create conditions suitable for peatland plants (water management), with a score of −2.90 ± 0.19. The CIs were reasonably consistent across all mean scores and smaller than those associated with the mean expert effectiveness scores indicating a higher level of consensus between the farmers in determining levels of economic cost.

3.5. Effectiveness and practicality combined

Mean practicality and economic cost scores are plotted for cross-comparison in Fig. 7. Measures considered to be both practical to implement, with a low economic cost to the farm, occupy the top right-hand quadrant of Fig. 7; these predominantly include mitigation measures from the nutrient management, regenerative management and farm machinery usage categories. Measures considered impractical to

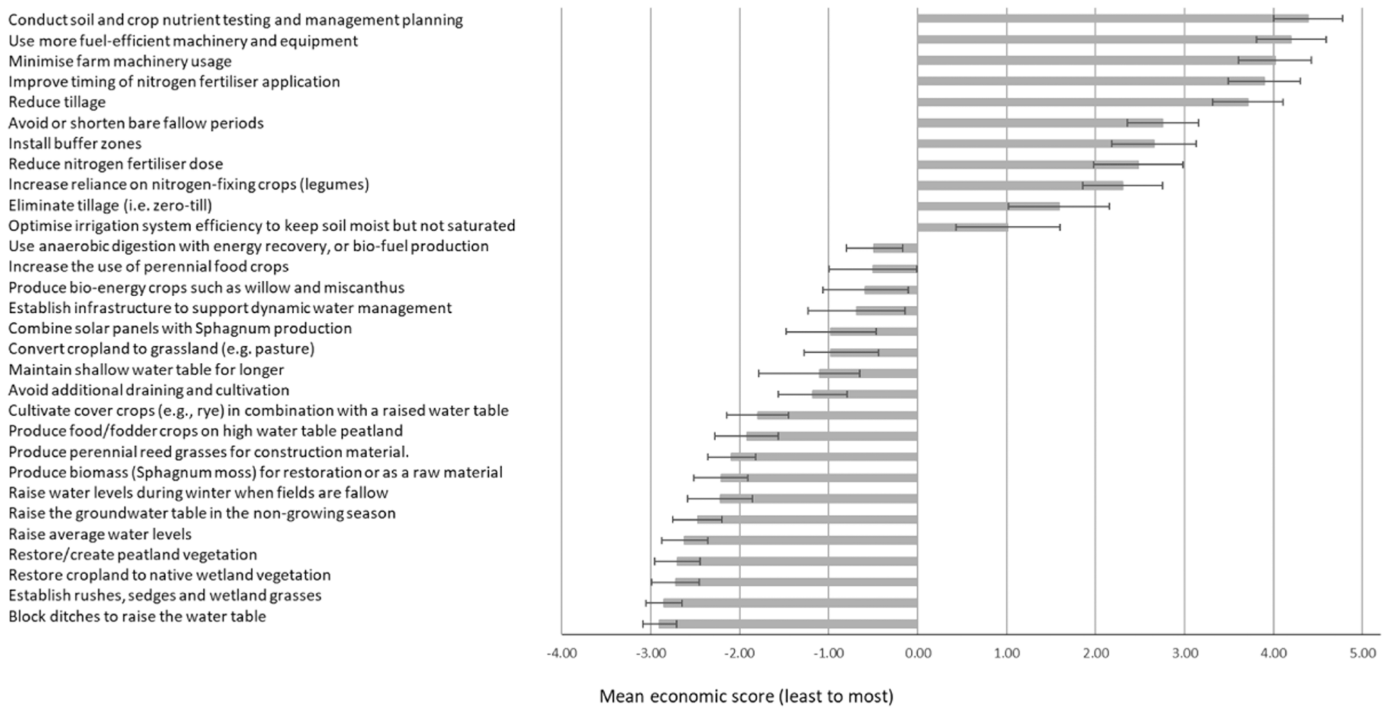

Fig. 6. Mean estimates of the economic scores across all farmers for the 26 shortlisted mitigation measures. The error bars represent 95 % confidence intervals of the mean scores. Values represent n = 121. The scores were rescaled to sum 100 across all thee mitigation measures to aid interpretation.

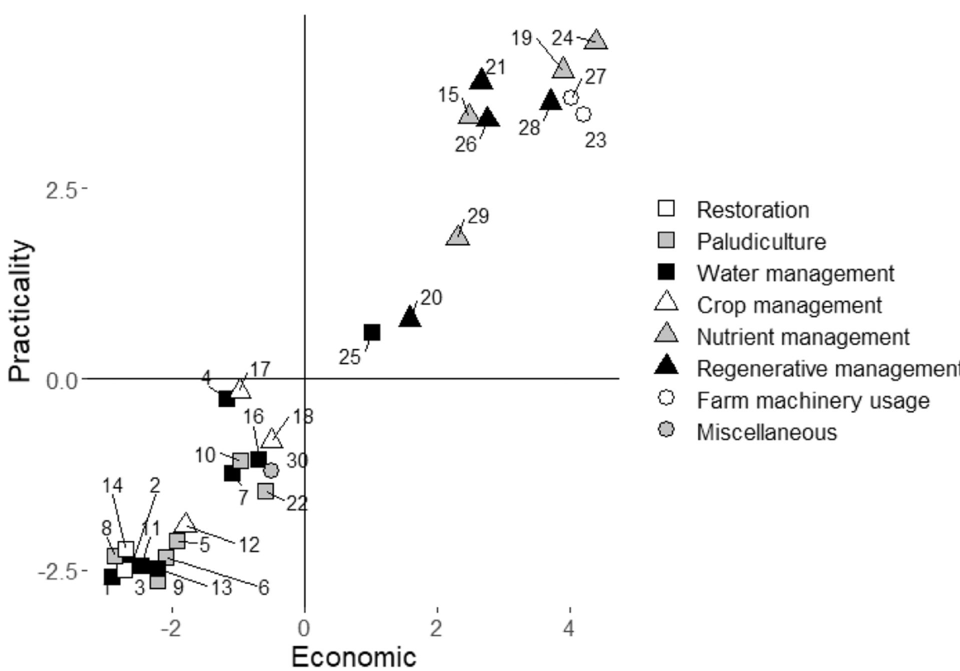

Fig. 7. Zero-centred scatter plot of mean practicality and economic cost for the 30 mitigation measures, categorised by mitigation type.

implement on the farm with a high economic cost occupy the bottom-left quadrant of Fig. 7. These predominantly include mitigation measures from the restoration, paludiculture, and water management categories.

Mean effectiveness and practicality scores are plotted for cross-comparison in Fig. 8. Measures considered effective at reducing GHG emissions, but impractical to apply on the farm, occupy the bottom right-hand quadrant of Fig. 8. These predominantly include mitigation measures from the restoration, paludiculture, water management categories. Measures considered practical to implement on the farm but ineffective at reducing GHG emissions occupy the top-left quadrant of Fig. 8. These predominantly include mitigation measures from the crop management, nutrient management regenerative management and farm machinery usage. Measures considered ineffective and impractical occupy the bottom-left quadrant and include mitigation measures from across various categories. There are no mitigation measures considered to be both practical and effective (top-right quadrant).

Mean effectiveness and economic cost scores are plotted for cross-comparison in Fig. 9. Measures considered effective at reducing GHG

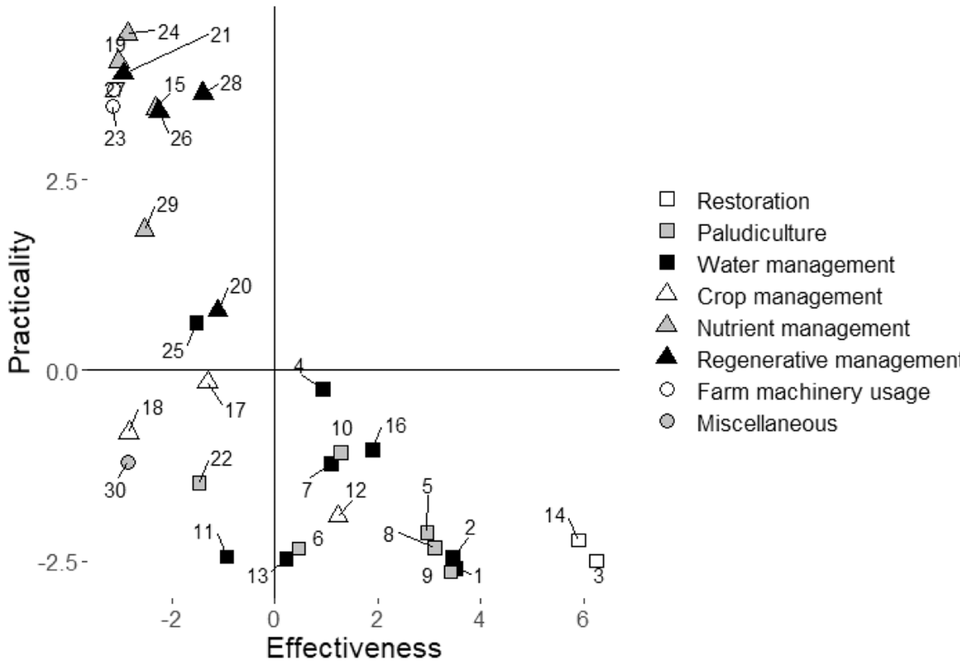

Fig. 8. Zero-centred scatter plot of mean effectiveness and practicality for the 30 mitigation measures, categorised by mitigation type.

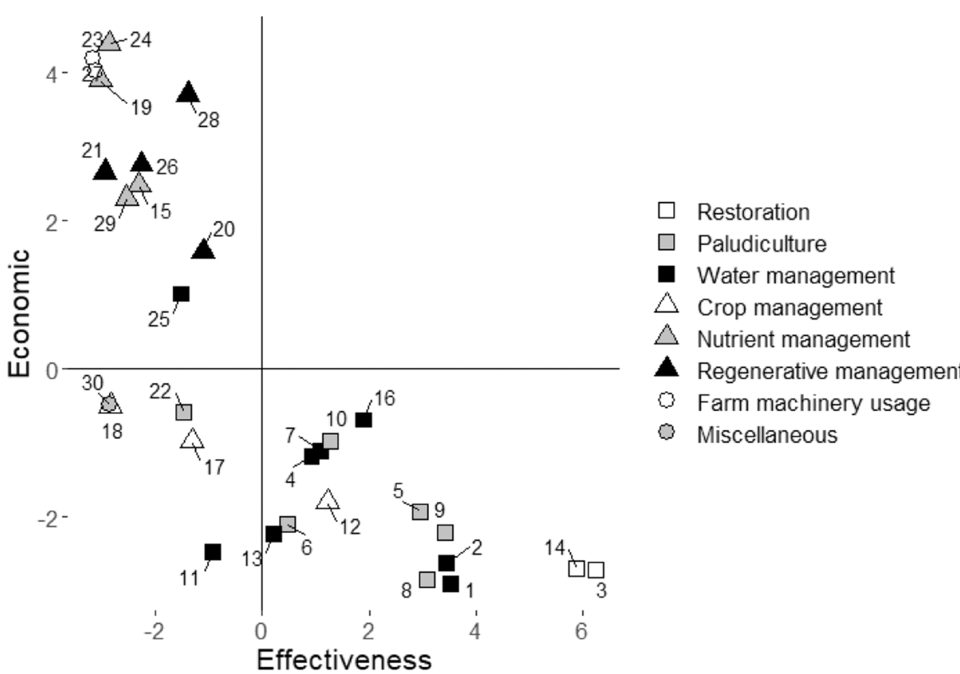

Fig. 9. Zero-centred scatter plot of mean effectiveness and economic cost for the 30 mitigation measures, categorised by mitigation type.

emissions, but with a high economic cost to the farm, occupy the bottom right-hand quadrant of Fig. 9. These predominantly include mitigation measures from the restoration, paludiculture and water management categories. Measures considered low cost to implement on the farm but ineffective at reducing GHG emissions occupy the top-left quadrant of Fig. 9. These predominantly include mitigation measures from the nutrient management, regenerative management, and farm machinery usage categories. Measures considered ineffective and costly occupy the bottom-left quadrant and include mitigation measures from across various categories. There are no mitigation measures considered to be effective with a low economic cost (top-right quadrant).

3.6. Heterogeneity in farmer responses

3.6.1. Frequency distributions of respondent scores

The degree of consensus between individual respondents can be inferred from the distributions of individuals' mean scores. In Section 3.5 we show there are no occurrences where mitigation measures are considered to be both effective and practical, or effective with low economic cost. There are however 11 mitigation measures assessed by farmers to be practical to implement with low economic cost to the farm. To assess variation in farmers' perceptions of practicality and economic cost for each of the mitigation measures featured in the upper right quadrant of the economic-practicality space (Fig. 9), the number of respondents were plotted against the practicality/economic score they ascribed to the mitigation measure (Fig. S1 a-j). The profile of the frequency distributions of individual level practicality scores for each mitigation measure reveals the degree of agreement amongst farmers, where a positive skew indicates high agreement and a negative skew high disagreement. There was a particularly high level of consensus amongst farmers on mitigation measure 24 (Conduct soil and crop nutrient testing and management planning); mitigation measure 19 (Improve timing of nitrogen fertiliser application); mitigation measure 27 (Minimise avoidable use of farm machinery); mitigation measure 23 (Use more fuel-efficient machinery and equipment); mitigation measure 28 (Reduce tillage) and mitigation measure 21 (Install buffer zones) for both practicality and economic cost (Fig S1. a-f). Similarly, there was high agreement for practicality on mitigation measure 26 (Avoid or shorten bare fallow periods) and mitigation measure 15 (Reduce nitrogen fertiliser dose). On economic costs for these mitigation measures the scores were more widely distributed (Fig. S1 g-h) suggesting a weaker agreement amongst farmers but still some level of agreement. Similarly we observed this for both practicality and economic cost for mitigation measure 29 (Increase reliance on nitrogen-fixing crops) (Fig. S1 i). Despite above-average mean scores on mitigation measure 20 (Eliminate tillage (i.e. zero-till)) and mitigation measure 25 (Optimise irrigation system efficiency to keep soil moist but not saturated), individual-level scores indicate higher levels of disagreement between farmers on

Table 4
Results of Kruskal-Wallis tests with Dunn's test with Bonferroni correction pairwise comparisons for the practicality and economic survey categories showing where there are significant differences between subgroups in practicality and economic mean scores in responses to a Best/Worst Scaling survey.

			Kruskal-Wallis Test				Dunn's test with Bonferroni correction	
Survey category	Demographic	Mitigation measure	Test statistic (H)[a]	Degree of freedom	Sig.	Epsilon square (ε^2)	Sub-category	Adj. Sig.
Practicality	Postcode Area	Restore cropland to native wetland vegetation	24.73	4	<0.01	0.18	Fens-Humberhead Levels	0.04
		Establish rushes, sedges and wetland grasses	22.89	4	<0.01	0.16	Fens-Humberhead Levels	0.02
		Restore/create peatland vegetation	29.60	4	<0.01	0.21	Fens-Humberhead Levels	<0.01
		Convert cropland to grassland (e.g. pasture)	19.10	4	<0.01	0.14	Fens-North West	0.02
	Farm Type	Restore cropland to native wetland vegetation	17.56	4	<0.01	0.13	Mixed arable/ horticulture-Other	0.01
							Arable-Other	<0.01
		Establish rushes, sedges and wetland grasses	18.79	4	<0.01	0.13	Mixed arable/ horticulture-Other	0.01
							Arable-Other	<0.01
		Restore/create peatland vegetation	15.28	4	<0.01	0.11	Mixed arable/ horticulture-Other	<0.01
							Arable-Other	0.05
		Convert cropland to grassland (e.g. pasture)	30.59	4	<0.01	0.22	Mixed arable/ horticulture-Other	<0.01
							Arable-Other	<0.01
	Farm Size	Avoid additional draining and cultivation	8.52	3	0.04	0.06	500 + ha-200–499 ha	0.03
		Convert cropland to grassland (e.g. pasture)	8.74	3	0.03	0.06	200–499 ha-< 100 ha	0.03
		Increase the use of perennial food crops	12.23	3	<0.01	0.09	500 + ha-100–199 ha	0.04
							200–499 ha-< 100 ha	0.05
	Total Peat	Produce food/fodder crops on high water table peatland	8.93	3	0.03	0.06	200–499 ha-< 100 ha	0.04
	Depth of Peat	Produce perennial reed grasses for construction material	10.85	3	0.03	0.08	> 60 cm-Unsure	0.04
	Age	Convert cropland to grassland (e.g. pasture)	12.20	3	0.02	0.09	35–44-> 55	0.04
Economic	Gender	Fill/block ditches	13.05	3	<0.01	0.11	Male-Female	<0.01
		Raise average water levels	13.90	3	<0.01	0.12	Male-Female	<0.01
		Avoid additional draining and cultivation	9.83	3	<0.01	0.08	Male-Female	0.01
		Raise water levels during winter when fields are fallow	11.04	3	<0.01	0.09	Male-Female	0.03
	Farm Type	Restore cropland to native wetland vegetation	12.53	4	0.01	0.10	Mixed arable/ horticulture-Other	0.02
		Restore/create peatland vegetation	10.81	4	0.03	0.09	Mixed arable/ horticulture-Other	0.02
		Convert cropland to grassland (e.g. pasture)	24.57	4	<0.01	0.20	Other horticulture-Other	0.05
							Mixed arable/ horticulture-Other	<0.01
	Postcode area	Restore cropland to native wetland vegetation	17.17	4	<0.01	0.14	Fens-North East	0.05
		Convert cropland to grassland (e.g. pasture)	30.01	4	<0.01	0.25	Fens-North West	<0.01
							Fens-North East	0.02
		Increase the use of perennial food crops	12.57	4	0.01	0.10	Fens-North West	0.01
	Farm Size	Avoid additional draining and cultivation	9.82	3	0.02	0.08	500 + ha-< 100 ha	0.02

the practicality and economic cost of these mitigation measures. (Fig S1 j-k).

3.6.2. Comparison of scores between subgroups

In a further assessment of heterogeneity in farmer perceptions of effectiveness, practicality and economic cost, the distribution of scores between subgroups of both experts and farmers, based upon demographic data (Table 4), were compared and discussed in the discussion. No significant differences were found between subgroups of experts ($p > 0.05$) but significant differences were found between some farmer subgroups in both practicality and economic scores.

3.6.2.1. Practicality scores. Kruskal-Wallis tests with post-hoc test using Dunn's test with Bonferroni correction showed location (between the Fens and the Humberhead Levels and the Fens and the North West); farm type (between mixed arable/horticulture and other farm types and arable and other farm types); farm size (between 500 + ha and 200–499 ha farms and 200 – 499 ha and 100 – 199 ha farms total peat (between 200 and 499 ha and <100 ha of peat); depth of peat (between >60 cm peat and those who were unsure) and age, (between those aged 35 – 44 and those > 55) were significant factors in the scores for practicality on some mitigation measures (Table 4; supplementary material 1.1).

3.6.2.2. Economic scores. Kruskal-Wallis tests with post-hoc test using Dunn's test with Bonferroni correction showed gender (between male and female farmers); farm type (between Mixed arable/horticulture and other farm types and other horticulture and other farm types) and location (between the Fens and the North East and the Fens and the North West) (mitigation measure 17, $p < 0.01$, medians, 0.30/1.62) were significant factors in the scores for economic cost on some mitigation measures (Table 4; supplementary material 1.2).

4. Discussion

4.1. Comparing effectiveness, practicality and economic cost

The two mitigation measures ranked as being the most effective at reducing GHG emissions were both in the restoration category, namely, 3: Restore cropland to native wetland vegetation and 14: Restore/create peatland vegetation. The expert panel in this study ranked the mitigation measures on their individual effectiveness at reducing GHG emissions at a farm scale. These rankings are consistent with other studies which show that to completely halt CO_2 emissions from agriculturally utilised peatlands, it would be necessary to either fully restore them to wetland ecosystems or adopt wetter farming mitigation measures such as those associated with paludiculture (Evans et al., 2019). Drained and cultivated fen peats represent some of the world's most productive soils (Taft et al., 2018), therefore, the potential socio-economic consequences of rewetting are much higher than on less productive upland agricultural soils (Freeman et al., 2022; Mulholland et al., 2020). The low farmer scores for practicality and economic cost indicate that farmers deem these C emission mitigation measures to be impractical to implement and costly. Low practicality and negative economic cost scores were also assigned to the other 7 mitigation measures ranked most effective at reducing GHG emissions: paludiculture (9: Produce biomass (Sphagnum moss) for restoration or as a raw material; 8: Establish wetland species such as rushes, sedges and wetland grasses for the production of animal litter and 5: Produce food/fodder crops on high water table peatland); water management (2: Raise average water levels and 1: Block ditches to raise water levels) and crop management (12: Cultivate cover crops (e.g., rye) in combination with a raised water table).

In contrast, the 4 mitigation measures ranked most practical to implement with the least economic cost (24: Conduct soil and crop nutrient testing and management planning; 19: Improve timing of nitrogen fertiliser application; 15: Reduce nitrogen fertiliser dose and 29: Increase reliance on nitrogen-fixing crops (legumes)) are all in the nutrient management category and all have low scores for effectiveness.

A comparison between effectiveness scores and practicality and economic cost scores found no mitigation measures to be ranked both effective and practical, or effective with low economic cost highlighting the difficulties faced by policy makers looking to meet Net Zero carbon targets through the re-wetting of 25 % of lowland peat by 2050 (Committee on Climate Change UK, 2020). Whilst water management and paludiculture mitigation measures may be effective at reducing GHG emissions, they face several implementation barriers. These include; high upfront costs for implementation; high opportunity costs associated with lost agricultural production; a perceived need to keep land permanently drained for flood management; and a lack of knowledge and skills among farmers and landowners to use and manage land differently (e.g. shifting from conventional crops to 'wet-farming'; Committee on Climate Change UK, 2020). Furthermore, their implementation has the potential to impact UK food production, which could result in the 'off-shoring' of GHG emissions; unless this is offset by increased UK production on mineral soils (Evans et al., 2019).

Truly 'sustainable' agricultural management may be unachievable on highly productive lowland soils (Wijedasa et al., 2016) but there are mitigation measures, which, if implemented, could reduce GHG emissions below their current levels. Changes in farm management practices that minimise soil disturbance, and/or changes in crop selection (particularly to enable higher water tables to be maintained) will reduce CO_2 emissions, yet only these will only be marginal without implementing higher water table management, whilst measures that limit the use of nitrogen fertilisers are likely to reduce N_2O emissions with significant benefits for total GHG emissions (Leppelt et al., 2014; Lin et al., 2022). Here we show several mitigation measures ranked by farmers as being both practical to implement and having a low economic cost to the farm. These include all 4 of the nutrient management mitigation measures; both of the farm machinery usage measures; all four of the regenerative management measures, and measure 25: Optimise irrigation system efficiency to keep soil moist but not saturated (water management). Individually, these mitigation measure scored low for effectiveness and cannot be expected to halt C loss from cultivated peatlands. On the other hand, a combination of reduced soil disturbance, improved nutrient management and use of legumes, optimisation of irrigation systems and more efficient fossil fuel usage would be expected to make some contribution to reducing overall GHG emissions from current levels, however, again these savings are marginal without wetter farming practices.

4.2. Heterogeneity in expert and farmer responses

The mitigation measures ranked most effective by experts in the BWS survey are comparable with those scored by the expert panel who shortlisted the initial mitigation measure list to the 30 used in the survey (Section 2.2). The actual rankings may differ slightly, but mitigation measures identified during shortlisting as most effective, are also ranked most effective in the BWS survey, showing a high level of agreement between the panel and the respondents to the survey. In the farmer surveys, analysis of the distribution of individual level scores for the 11 mitigation measures ranked as practical with a low economic cost, showed a high level of consensus across all of the mitigation measures with the exception of mitigation measure 20: Eliminate tillage (i.e. zero-till) and mitigation measure 25: Optimise irrigation system efficiency to keep soil moist but not saturated, where there is more disparity in responses.

The UK's exit from the European Union and the Common Agricultural policy has seen a reduced emphasis on direct subsidies (e.g., land hectare, and a move towards a 'public money for public goods' approach via the introduction of an Environmental Land Management Scheme (ELMS) in England (DEFRA, 2018b). This fundamental change to agricultural policy is expected to see farm business income drop across all farming sectors (AHDB, 2019) but there may be opportunities to replace some of this income loss with public goods payments through ELMS (DEFRA, 2018b). On the other hand, as farm income decreases, farmers may be reluctant to take significant amounts of land out of production, especially to deliver mitigation measures involving re-wetting and restoration of native wetland species, which they deem to be impractical or to have a high economic costs to the farm business. The level of agreement between farmers on the 11 mitigation measures ranked high for both practicality and low economic costs means that farmers will be more likely to implement these mitigation measures, should they be available through ELMS, but based on the expert consultation undertaken these mitigation measures are expected to offer limited mitigation of ongoing C loss from agricultural peat.

4.3. Comparisons of scores between subgroups

Our analysis showed no significant differences ($p > 0.05$) between expert subgroups in ranking scores for effectiveness. They did show some significant differences between the farmer subgroups in some rankings for practicality and economic cost. However, it was clear from the analysis that the majority of the water management, and all of the paludiculture mitigation measures, were consistently ranked as being impractical, and with a high negative economic cost on the farm business. The only clear divergence in views was in relation to the conversion of cropland to grassland (mitigation measure 17), with respondents from Northwest England (where grassland is extensive, alongside areas of arable and horticulture) responding more positively than farmers in the Fens of Eastern England, where cropland agriculture dominates. While this suggests some potential to mitigate emissions via changes in land-use, it should also be noted that there is a risk that reduced CO_2 emissions resulting from higher water levels under grassland versus cropland could be offset by higher N_2O and CH_4 emissions in the presence of ruminant livestock (e.g. Wen et al., 2021). Apart from this notable divergence in attitudes to grassland agriculture, the lack of significant difference between the subgroups across most of the mitigation measures, is indicative of a high level of consensus among different farmer groups.

Although this study has clearly highlighted key issues and challenges associated with mitigating GHG emissions and C loss from lowland peatland, we acknowledge the limitations of the study. Firstly, it would have been beneficial to survey a larger number of land managers to reduce the uncertainty associated with the choice of different mitigation measures. Secondly, we could have included other regions of the UK, and Europe, where cultivated peat soils occur to gain better geographical coverage. Thirdly, after deployment, the efficacy of each mitigation measure is expected to change over time in terms of its C mitigation potential (i.e. short- vs. long-term C gains), however, we set no time boundary for respondents. In this study, we also did not ask respondents to include the secondary impacts of each mitigation measure beyond the farm boundary (e.g. use of paludiculture products), however, clearly this is of importance in the overall deployment of alternative land uses. In future studies it would therefore be good to benchmark each of the mitigation measures by undertaking a full life cycle and economic assessment. Our study may have included some bias associated with the final choice of mitigation measures due to the expertise of the expert panel. In addition, we did not include potential future, but unproven, technologies (e.g., use of novel genetically engineered plants with high waterlogging tolerance or C storage potential) or consider the impact of future climate change scenarios or policy interventions which might affect the long-term viability of some mitigation options.

5. Conclusions

Although drained agricultural lowland peat landscapes are deeply unsustainable, they are highly productive landscapes which make significant contributions towards food security. Mitigation measures aimed at increasing soil wetness were widely viewed as essential to reducing carbon emissions and carbon losses from lowland peat by experts whilst these measures were consistently viewed negatively by farmers (particularly when associated with cessation of food production). Reconciling the divergence between views through the development of policy and finance mechanisms to support wetter modes of farming, without leading to overall loss of income or food production, represents a major ongoing challenge not only in the UK, but across many countries in Europe, Southeast Asia and beyond. Addressing this challenge is essential if countries are to meet their Net Zero targets, and if the substantial fraction of global anthropogenic greenhouse gas emissions generated by drained peatlands is to be reduced.

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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

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2023.106886.

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