Impact of local and national policies to reduce agriculture-related air pollution through improving diet and farm management: the AMPHoRA mixed methods study

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Extended Research Article

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This article

Abstract

Methods: This study employed an interdisciplinary approach to assess the impact of agricultural production modifications and dietary changes on ammonia emissions, health outcomes and health inequalities. Statistical and econometric methods were applied to analyse agricultural emission trends and dietary patterns. Spatial data analysis and numerical modelling techniques were used to simulate the dispersion and transformation of atmospheric pollutants. Health impact modelling estimated mortality and morbidity outcomes under various policy scenarios, while cost-effectiveness and cost–benefit analyses supported decision-making. A participatory approach involving multistakeholder engagement was utilised to enhance policy relevance and implementation feasibility.

A systematic scoping review of academic studies on agricultural-derived air pollution and clinically coded outcomes revealed very limited research on this topic, which presents an inconsistent picture as to whether agricultural-derived particulate matter affects health.

Results: Key findings indicate that dietary modifications have greater potential health benefits than direct reductions in particulate matter exposure from ammonia emissions. Small reductions in meat and dairy consumption, supported by taxation and subsidies, could help achieve environmental and health targets. A 20% meat and dairy tax, coupled with a 20% subsidy on fruits and vegetables, could reduce meat consumption by 21.5% and increase fruit and vegetable intake by up to 13.5%. These dietary shifts also significantly lower greenhouse gas emissions and water use.

While ammonia's environmental effects are well documented, its direct health impacts remain uncertain. Epidemiological studies suggest a possible association between ammonium-derived particulate matter and increased mortality and cardiorespiratory diseases, though findings are inconsistent. Toxicological assessments indicate limited intrinsic toxicity of ammonium nitrate and sulfate. A 'high-ambition mitigation' scenario integrating ammonia reduction measures with dietary shifts could prevent 67,000 premature deaths and 270,000 cases of respiratory diseases over 30 years. Notably, older adults and lower-income populations would experience the greatest health benefits. Most farm-based ammonia reduction strategies demonstrated net economic benefits, with only a few measures having limited abatement potential. Additionally, reduced greenhouse gas emissions further amplified the benefits of each scenario.

Limitations: Despite robust modelling techniques and multistakeholder engagement, several limitations exist. The direct health effects of ammonia-derived particulate matter remain an area of uncertainty, necessitating further epidemiological research. Additionally, while economic and environmental benefits were quantified, behavioural responses to policy interventions – such as consumer acceptance of dietary changes – require further exploration. The study primarily focused on UK-specific data, limiting generalisability to other regions with different agricultural practices and policy landscapes. Finally, unintended consequences of dietary shifts on food security and cultural preferences were not fully explored, indicating the need for future research to refine policy recommendations.

The Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture project provides a comprehensive, interdisciplinary framework for evaluating integrated policy measures. It underscores the importance of sustainable agricultural and dietary transitions in achieving cobenefits for public health and environmental sustainability, while emphasising the need for continued research to address remaining uncertainties.

Future work: More detailed spatial and temporal analyses are required to fully understand the potential importance of significant local sources on human health in specific areas/times of year. There is a need to better align evidence of studies, such as Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture, with toxicological studies which suggest that (pure) ammonium nitrate and sulfate have only very modest toxicity.

Study registration This study is registered as PROSPERO CRD42020172116.

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Supplementary material can be found on the NIHR Journals Library report page (https://doi.org/10.3310/GJSR2325).

Supplementary material has been provided by the authors to support the report and any files provided at submission will have been seen by peer reviewers, but not extensively reviewed. Any supplementary material provided at a later stage in the process may not have been peer reviewed.

The supplementary materials (which include but are not limited to related publications, patient information leaflets and questionnaires) are provided to support and contextualise the publication. Every effort has been made to obtain the necessary permissions for reproduction, to credit original sources appropriately, and to respect copyright requirements. However, despite our diligence, we acknowledge the possibility of unintentional omissions or errors and we welcome notifications of any concerns regarding copyright or permissions.

List of abbreviations

AIM-HEALTH	Effectiveness of agricultural interventions to minimise the health impacts of air pollution (sister project to the AMPHoRA project)	ICD-10	*International Statistical Classification of Diseases and Related Health Problems*, Tenth Revision
AMPHoRA	Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture	IHD	ischaemic heart disease
		JNCC	Joint Nature Conservation Committee
AP	air pollutant	LRI	lower respiratory infection
BAU	business as usual	LY	life-year
BEIS	Department for Business, Energy & Industrial Strategy	MACC	marginal abatement cost curve
		MCDA	multi-criteria decision analysis
CBA	cost–benefit analysis	MRBRT	meta-regression–Bayesian regularized trimmed
CEA	cost-effectiveness analysis		
COGAP	Code of Good Agricultural Practice	NICE	National Institute for Health and Care Excellence
COMEAP	Committee on the Medical Effects of Air Pollutants	NPV	net present value
		ONS	Office for National Statistics
COPD	chronic obstructive pulmonary disease	PC	prostate cancer
COVID	coronavirus disease	PM	particulate matter
DA	devolved administration	$PM_{2.5}$	particulate matter with a diameter of ≤ 2.5 μm
DCE	discrete choice experiment		
DEFRA	Department for Environment Food and Rural Affairs	PPIE	patient and public involvement and engagement
DfT	Department for Transport	QALY	quality-adjusted life-year
ECHA	European Chemicals Agency	SIA	secondary inorganic aerosol
ECM	Electronic Contract Management	SMT	Scenario Modelling Tool
EHI	equivalised household income	SSB	sugar-sweetened beverages
EMEP4UK	European Monitoring and Evaluation Programme for the UK	T2DM	type 2 diabetes mellitus
		UKAMM	UK Agriculture Market Model
EoP	End of Project	UKCEH	UK Centre for Ecology & Hydrology
GBD	Global Burden of Disease		
GHG	greenhouse gas	VAT	value-added tax
GP	general practitioner	VOLY	value of a life-year lost
HMT	His Majesty's Treasury	WP	work package
ICD	*International Classification of Diseases*	WTP	willingness to pay

Plain language summary

Agriculture is a main driver of air pollution in the United Kingdom and other countries. This is because it is responsible for emissions of ammonia and other nitrogen compounds into the atmosphere from livestock farming, fertiliser use and other activities. These chemicals contribute to air pollution and are harmful to health, leading to heart and lung disease, stroke, cancer, type 2 diabetes and early death.

Solutions to reduce agricultural emissions and improve air quality and health can also support people's efforts to eat healthier diets and reduce greenhouse gas emissions from food production. Such solutions were the focus of the Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture project.

Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture evaluated the impact on health of past and future policy options. This was in order to see how policies could work together to:

- reduce agriculture-related air pollution
- to support healthy eating and
- act on climate change.

It took account of the interconnections between how people eat, farming and agricultural production, and the social and economic consequences of policies.

The project developed a list of existing and future policy actions and looked at different ways of improving agricultural technology, land-use management and other factors. It studied their impact on air pollution, United Kingdom diets and nutrition, and greenhouse gas emissions. Computer models calculated impacts on health arising from the effects of lower air pollution and better diets. Lastly, it compared the costs of policy interventions to the benefits they create.

From the start, Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture involved the public and other key stakeholders to give guidance to the project. We involved policy-makers, regulators, farmers, food producers, retailers, health professionals and food/environment advocates to help Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture draw on many perspectives. We used this to craft research questions, analyse data and share results.

The project found that agricultural technologies and changing land-use practices could reduce air pollution and improve health in the United Kingdom. However, combining these actions with policies that encourage people to eat healthier diets with less meat and more fruits and vegetables could result in much larger benefits for health. The evidence gathered by Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture aims to shape policy. It will provide critical evidence for how efforts to reduce outdoor air pollution can play a lead role and support a holistic approach to human health.

Scientific summary

Background

Agricultural emissions of ammonia (NH_3) significantly contribute to the formation of secondary inorganic aerosols (SIAs), leading to widespread population exposure to ammonium nitrate and sulfate components of fine particulate matter (with a diameter of ≤ 2.5 μm) ($PM_{2.5}$). Unlike nitrogen dioxide (NO_2), SIA exhibits mid- and long-range transport properties, exposing populations to $PM_{2.5}$ far from emission hotspots. Addressing NH_3 emissions and their interaction with sulfur dioxide (SO_2) and nitrogen oxides (NO_x) is complex due to the diverse sources and meteorological dependencies influencing SIA formation. Consequently, policy interventions must consider both local and long-range effects, as local measures alone may not effectively reduce ambient concentrations.

Additionally, human dietary choices and their links to food production, public health and environmental sustainability are subjects of extensive research. This study investigates how modifications in agricultural production and food consumption patterns can mitigate agricultural emissions, reduce associated health impacts and address health inequalities. Specifically, it evaluates interventions aimed at minimising the negative health effects of outdoor air pollution from non-road traffic-related sources.

The UK Clean Air Strategy and the Code of Good Agricultural Practice (COGAP) outline measures to reduce NH_3 emissions from agriculture by 2030. Reports such as the EAT–Lancet Commission on sustainable diets emphasise the necessity of dietary changes to ensure food security, nutrition and planetary health. Implementing technical and managerial interventions in agriculture and modifying dietary habits will influence NH_3 emissions and other pollutants. Comprehensive ex-ante assessments of policy interventions are essential to optimise environmental and human health benefits while safeguarding UK food security and nutrition. Following Brexit, environmental, agricultural and health policy reviews provide opportunities for an integrated approach to maximise public health and environmental and economic benefits. Reducing air pollution exposure, improving diets and enhancing nutrition could yield significant healthcare cost savings across the UK's health system.

State of knowledge

The adverse health effects of $PM_{2.5}$ are well documented. The Committee on the Medical Effects of Air Pollutants has extensively reviewed particulate air pollution and mortality, while the UK Air Quality Expert Group identified reductions in NH_3 and primary $PM_{2.5}$ emissions as the most effective strategies for reducing overall $PM_{2.5}$ concentrations. Agricultural activities accounted for 82% of the UK's total NH_3 emissions in 2016, making agriculture a critical sector for targeted interventions.

International case studies from the Netherlands, Germany and Denmark provide valuable insights into the effectiveness of technical and managerial interventions for NH_3 mitigation. The United Nations Economic Commission for Europe Air Convention's Task Force on Reactive Nitrogen has informed COGAP's recommended interventions, serving as a foundation for an integrated assessment in the UK.

Dietary patterns have well-established links to health and environmental outcomes. The Global Burden of Disease study attributed 11% of the total disease burden in England to dietary risks, with costs to the NHS estimated at £5.8B annually – surpassing costs associated with obesity, smoking and alcohol consumption. Major diet-related diseases include coronary heart disease, stroke, cancer and type 2 diabetes. Furthermore, agriculture contributes 10% of the UK's greenhouse gas (GHG) emissions. Shifting towards healthier diets could reduce GHG emissions by 17% and decrease premature mortality from non-communicable diseases.

While most research on sustainable diets focuses on climate change mitigation, air quality and nitrogen emissions have received comparatively little attention. Studies suggest that reducing animal-based food consumption could lower

nitrogen emissions by up to 40%. The European Nitrogen Assessment has quantified the diverse impacts of livestock on air, water, soil pollution and climate change, reinforcing the need for a comprehensive, integrated approach to assess dietary and agricultural interventions.

Objectives

The project aimed to:

1.   Convene a multistakeholder group, including policy-makers, industry experts, third-sector organisations and academics, to assess existing and potential policies for reducing air pollutants (APs) and GHG emissions via agricultural and dietary changes.
2.   Quantify the nutritional impacts of interventions altering food consumption patterns and UK production to enhance health and environmental sustainability.
3.   Evaluate the effects of these policies on APs (NH_3, NO_2, $PM_{2.5}$, ozone) and GHG emissions, now and under future policy scenarios.
4.   Develop health impact models to assess the morbidity and mortality effects of changes in air quality, agricultural interventions and dietary shifts.
5.   Compare policy scenarios using cost-effectiveness and cost–benefit analyses, incorporating health, economic and environmental factors up to 2050.
6.   Examine policy implications for implementation, patient health and public engagement through iterative stakeholder consultations.

Methods

- Work package (WP)1: quantified agricultural emission reductions using statistical modelling of production systems.
- WP2: analysed dietary trends and projected future scenarios using autoregressive methods and linear programming.
- WP3: applied spatial data analysis, geographical information systems and atmospheric modelling to simulate pollution dispersion.
- WP4: conducted health impact assessments using epidemiological data, systematic literature reviews and statistical modelling.
- WP5: performed economic valuations and cost–benefit analyses to assess intervention feasibility.
- WP6: integrated findings through participatory research methodologies, engaging diverse stakeholders to refine policy recommendations.

Results

- Dietary changes have greater human health benefits than reducing NH_3-related $PM_{2.5}$ exposure alone.
- NH_3 emissions contribute significantly to nitrogen deposition, degrading habitats. Dietary changes can simultaneously reduce NH_3 emissions and enhance human health.
- Moderate dietary modifications (e.g. reducing weekly meat and dairy intake) could help meet environmental targets while improving public health.
- A 20% meat and dairy tax, coupled with a 20% fruit and vegetable subsidy, could decrease UK meat consumption by 21.5%, while plant-based analogues could reduce it by 30.4%. Fruit and vegetable intake could rise by 3–13.5%.
- 'High-ambition mitigation' scenarios, aligned with the UK Climate Change Committee's Balanced Pathway, could prevent 13,000 premature deaths and 270,000 cases of respiratory diseases over 30 years. Dietary changes combined with NH_3 reductions could avert 67,000 deaths in the same period.
- Older adults and low-income households would experience the greatest health benefits.
- Most farm-level NH_3 mitigation measures yield net economic benefits.
- Reducing GHG emissions amplifies the benefits of dietary and agricultural interventions.
- Engaging a multistakeholder group fostered broader awareness of air pollution, diet and health interconnections in the UK.

Conclusions

The Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture (AMPHoRA) project has provided a comprehensive, interdisciplinary assessment of the interactions between agriculture, air quality, dietary choices and public health. It has generated extensive data on current and future NH_3 emissions and their health implications while highlighting the need for further research into the direct health effects of agricultural emissions.

By integrating economic, health and environmental analyses, the study underscores the importance of considering dietary changes alongside technical interventions to maximise benefits. Additionally, engaging community stakeholders has reinforced the relevance of these issues at the grassroots level, demonstrating the effectiveness of participatory approaches in environmental health policy-making.

It should be considered that the originally designed project plan was substantially impacted by the COVID pandemic, and throughout the project, adjustments had to be made to account for restrictions, for example, around community engagement. Furthermore, the interactions between the members of the project team were affected by the loss of one of the coinvestigators and the effects of reduced opportunities for direct, effective collaborative working. The project team is heavily indebted to Professor Paul Wilkinson of the London School of Hygiene and Tropical Medicine for his contributions, guidance and input, without which AMPHoRA would not have been possible.

Study registration

This study is registered as PROSPERO CRD42020172116.

Funding

Chapter 1 Introduction

Rationale for research and background

Agricultural emissions of ammonia (NH_3), in particular, contribute substantially to the formation of secondary inorganic aerosols (SIAs), resulting in widespread population exposure to ammonium nitrate/sulfate components of fine particulate matter (with a diameter of ≤ 2.5 µm) ($PM_{2.5}$). Exposure to $PM_{2.5}$ affects much wider areas and populations far away from emission hotspots [compared to, e.g., nitrogen dioxide (NO_2) exposure] due to the mid- and long-range transport of SIA. Emissions of NH_3, and the formation of SIA with sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions, are more challenging to address by policy interventions, as emissions stem from a variety of sources and are notably affected by meteorological conditions. Hence, interventions may have both local and long-range effects, and local interventions may not necessarily be effective in reducing local ambient concentrations. At the same time, human diets and the relationships between food production and both human and environmental health are subject to extensive research. We addressed the key research question of the call *'Which interventions are effective in minimising the negative health impacts of outdoor air pollution from non-road-traffic-related sources?'* with a specific focus on how changes in agricultural production and patterns of food consumption can influence agricultural emissions, their negative health effects and health inequalities. Key topics we addressed include:

- Contribution of agricultural emissions of NH_3 and other air pollutants (APs) to the exposure of the UK population to harmful levels of $PM_{2.5}$.
- Effectiveness of existing and planned policy interventions to mitigate emissions and reduce exposure.
- Public health benefits in terms of cost savings and improving well-being of vulnerable population groups, patients and the general public.
- Impacts of interventions in terms of socioeconomic and environmental aspects, accounting for cobenefits and unintended consequences, with a focus on regional and distributional effects.
- Potential cobenefits of emission and dietary changes for greenhouse gas (GHG) emissions, biodiversity and non-communicable disease prevention.

The UK Clean Air Strategy,[1] as well as the Code of Good Agricultural Practice (COGAP) for reducing NH_3 emissions,[2] identify a range of policy interventions to reduce NH_3 emissions from agriculture in the UK by 2030. The EAT–Lancet Commission on healthy diets from sustainable food systems[3] and other recent research (e.g. Springman *et al.*)[4] have highlighted the need for substantial changes in human diets to safeguard food security, nutrition, human health and well-being within planetary boundaries. Both the implementation of technical and management interventions in agricultural production systems and changes in human diets will affect emissions of NH_3 and other APs. Such changes will vary between regions and agricultural subsectors. Full costs and benefits of policy interventions need to be modelled ex-ante, to ensure that interventions are designed for maximum positive environmental and human health effects, without negative impacts on UK food security and healthy nutrition. With the UK's exit from the European Union, environmental, agricultural and health policy reviews (e.g. Rapid Evidence Assessments)[5] present a unique opportunity for a consistent and integrated approach to maximise benefits for public health, the environment and the economy. Reducing exposure to harmful levels of air pollution and thus adverse public health effects, as well as improving diets and nutrition, could achieve whole health system cost reductions, benefiting patients and primary/secondary healthcare provisions. Our proposed research will realise a step change in how we conduct ex-ante integrated assessments of policy interventions.[6]

Evidence of public health impacts of particulate matter (PM) is well established, summarised by a Committee on the Medical Effects of Air Pollutants (COMEAP) report[7] on the effects of particulate air pollution on mortality in the UK. The Air Quality Expert Group has reviewed options for the 'Mitigation of United Kingdom $PM_{2.5}$ Concentrations'[8] and concluded that *'Reductions in emissions of primary $PM_{2.5}$ and NH_3 are the most effective in reducing $PM_{2.5}$ mass out of the five alternatives studied'*. In the UK, agricultural sources contributed 82% of total NH_3 emissions in 2016,[9] making interventions aiming at the reduction of agricultural emissions a viable pathway to reduce NH_3 and, consequently, population exposure to $PM_{2.5}$. Evidence from the Netherlands, Germany and Denmark[10–12] provides insights into the

effectiveness of technical/management interventions to reduce NH_3 emissions. Specific interventions for reducing NH_3 emissions (e.g. as identified by COGAP[2] based on international expert elicitation in the United Nations Economic Commission for Europe Air Convention's Task Force on Reactive Nitrogen[13]) are the starting point for an integrated assessment for the UK.

A well-established body of evidence links diets to impacts on both health and the environment. The Global Burden of Disease (GBD) study found that 11% of the total disease burden in England was from dietary risks, including low consumption of fruits, vegetables and whole grains, and high consumption of meat, sugar and salt.[14] Dietary risks in the UK are estimated to cost the NHS £5.8B a year,[15] more than obesity, physical inactivity, smoking and alcohol consumption. The main diseases responsible for this burden are coronary heart disease, stroke, cancer (particularly colorectal, stomach and oesophageal) and type 2 diabetes.

Other links between diets and other environmental impacts are evident, with agriculture contributing 10% of GHG emissions in the UK.[16] Recent studies show cobenefits for GHG emissions from moving to healthier diets in the UK,[17,18] with a healthy diet reducing emissions by 17% compared to current average diets and reducing premature deaths from non-communicable diseases. However, previous studies have focused mainly on GHG emissions at the expense of other environmental impacts. A recent study found 74% of papers examining sustainable diets had focused on climate change, while only 4% examined air quality and ozone depletion.[19]

The few previous studies that have explored links between diets and air pollution have found that reducing consumption of animal-based foods would reduce nitrogen emissions, in some cases by up to 40%.[20] For NH_3 and, more generally, reactive nitrogen emissions, the European Nitrogen Assessment[21] has quantified the varying contributions of different livestock categories to air, water and soil pollution and climate change. These studies highlight the need for a comprehensive, integrated assessment due to the complicated relationships between nitrogen impacts and health impacts from diets.

Aim and objectives

Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture (AMPHoRA) addressed the overarching research question:

> 'What contribution can emission reductions from agricultural production make to improving public health in the UK?'

It aimed to evaluate the health impact of food and agriculture strategies in the UK directed at improving outdoor air pollution, and how to align them with strategies for reducing chronic disease and improving environmental sustainability, including reductions of GHG emissions, and to understand barriers and opportunities for rapid implementation of policies at scale.

The following specific objectives were addressed in the project:

1. To convene a multistakeholder group – comprising government departments/agencies, food and agriculture industry experts, the public, third-sector organisations and academics – to delineate existing and potential future policies with potential to reduce emissions of APs and GHGs through changes to (1) agricultural technology and land-use management and (2) factors influencing dietary patterns **[work package (WP) 1]**.
2. To quantify the impact in terms of key nutritional constituents and fulfilment of nutritional needs of interventions aimed at altering patterns of food consumption and UK production that both help to reduce AP emissions and improve diets for health and sustainability (**WP2**).
3. To quantify the impact of such policies on APs, on GHG emissions and on population-weighted ambient concentrations of PM, NO_2 and ozone, now and in future, under policy scenarios defined in (1) (**WP3).**

4. To develop and apply models of health impact capturing the mortality and morbidity benefits/harms of changes in air quality of food/agriculture interventions (including both existing and potential future policies), and of the associated dietary changes and environmental impacts where relevant (**WP4**); a specific part of WP4, the **scoping review (WP4.1)**, had the objective to conduct a systematic search of the literature to evaluate the impact of NH_3 and NH_3-derived PM on human health using classified clinical outcomes.

5. To compare policies over time horizons up to 2050 using a multi-criteria assessment framework with assessment criteria developed with the multistakeholder group (and to include the fulfilment of AP goals, health, health differentials, GHG emissions targets, economic costs) (**WP5**).

6. To assess the implications of these analyses for policy development and implementation, patients and the wider public, taking account of real-world constraints and opportunities, including with the aid of an iterative cycle of stakeholder engagements (**WP6**).

Chapter 2 Methods

Reducing ammonia emissions from UK agriculture

Estimating agricultural ammonia emissions

The NH_3 emission inventory model for UK agriculture, as used to develop national emission estimates for international reporting, was used as the basis for developing emission scenarios in this project. A base year of 2019 was used, being the most recent year from the 2021 national inventory submission (1990–2021) available at the outset of the project. Specific details of the model, parameter values and underlying data as used in that submission are given by Misselbrook and Gilhespy.[22] Briefly, the model combines detailed activity data relating to livestock numbers, crop areas and farming management practices with activity-specific NH_3 emission factors, as derived from UK studies, to estimate national emissions at a devolved administration (DA) level. The UK Scenario Modelling Tool (SMT), developed under Department for Environment Food and Rural Affairs (DEFRA) project Electronic Contract Management (ECM) 55618, was used to model the emission estimates for all scenarios, with the 2019 inventory estimate as the base. The SMT enables changes to be made to the underlying livestock numbers and crop areas, to nitrogen excretion rates by different livestock types, for example, through changes in livestock diet and/or productivity, and the introduction of specific farming practices and technical measures designed to reduce NH_3 emissions.

Ammonia mitigation measures

Approximately 75% of NH_3 emissions from agriculture arise from the excretion and subsequent management of livestock manure, and the magnitude and rate of emission is influenced by the strength of the source (amount of ammoniacal nitrogen present), the exposed surface area, the potential of hydrogen (pH) (emissions being greater for a higher pH) and the air flow conditions above the exposed surface area. Manipulation of these factors is the basis for most on-farm mitigation measures through the management stages of livestock housing, manure storage and manure application to land. Nitrogen fertilisers as applied to crops and grassland are the other major emission source. Fertiliser type is of particular importance, with urea-based fertilisers being associated with higher emissions than other types. Mitigation measures can therefore include the inclusion of a urease inhibitor with urea fertiliser, substitution of urea with other fertiliser types, and/or an overall reduction in the use of nitrogen fertilisers. Further details of the range of specific mitigation measures available and their effectiveness can be found in Bittman *et al.*,[23] Misselbrook and Gilhespy (see the appendix)[22] and, specifically for those included in the SMT (together with estimated costs), in the documentation supporting that model (DEFRA ECM 55618).

Agricultural scenarios

The base scenario (scenario 1; refer to *Table 1* for the list of the scenarios) was the current (2019) emission estimate for UK agriculture. A second scenario (scenario 2) was developed, in which all current implementation of mitigation measures was removed (set to zero in the SMT), to provide an indication of the level of reduction currently achieved by the agricultural sector through uptake of existing measures. Scenario 3 provided a 'business as usual' (BAU) projection based on the 2019 year estimate, but with livestock numbers and crop areas (and hence nitrogen fertiliser applications) modified according to the activity data projections provided by the DEFRA UK Agriculture Market Model (UKAMM) in September 2020. There was also an assumed increase in milk yield per dairy cow, resulting in greater nitrogen excretion per cow. Implementation of mitigation measures in the model remained exactly as for the 2019 estimate; that is, there was an assumption of no further uptake of mitigation methods or practices between 2019 and 2030 under the baseline scenario.

Two agricultural emission reduction scenarios were developed (scenarios 4 and 5), based on the 2030 projection (scenario 3), with either a medium- or high-ambition level of mitigation measure implementation. The medium-ambition agricultural intervention scenario (scenario 4) was based on the measures proposed in DEFRA's Clean Air Strategy[1] (DEFRA 2019, see Chapter 7 for Agriculture) with DA engagement as part of the Nitrogen Futures project [Joint Nature Conservation Committee (JNCC) Report No. 665], with measure uptake rates as shown in *Table 2*. In addition to the measures shown in *Table 2*, a 5% reduction in nitrogen fertiliser use on grassland and crops was included to account for improved manure nutrient use and some uptake of improved practices, such as precision application.

TABLE 1 Scenario names and descriptions

Scenario number	Scenario name	Description
1	Present day (2019)	The estimate of NH_3 emissions from UK agriculture for 2019 as reported in the UK Air Quality Pollutants Inventory national submission 2021, covering the years 1990–2019
2	2019 with current agricultural emission measures removed	Current uptake of NH_3 mitigation measures is set to zero; comparison with scenario 1 shows what has been achieved to date through implementation of technical mitigation measures
3	Current market trend to 2030	A BAU projection for the agriculture sector assuming current (2019) rates of implementation of mitigation measures but with livestock numbers and crop areas based on forecasts from the UK Agricultural Market Model (DEFRA, September 2020)
4	Lower emissions from farms – medium ambition 2030	Medium-ambition uptake of mitigation measures on farms based on the DEFRA Clean Air Strategy proposal
5	Lower emissions from farms – high ambition 2030	High-ambition uptake of mitigation measures on farms, improvements in agronomic efficiencies and reductions in food waste (pre and post farm gate) based on measures included in the Climate Change Committee's Balanced Pathway to Net Zero
6	Human diet trend to 2030 – no export limits	Livestock numbers and crop areas for 2030 based on UK human dietary trends and market projections, with no limits on export of UK agricultural commodities
7	Human diet trend to 2030 – with export limits	Livestock numbers and crop areas for 2030 based on UK human dietary trends and market projections, but with limits to the quantities of UK agricultural commodities exported
8	Human diet trend to 2050 – no export limits	Livestock numbers and crop areas for 2050 based on UK human dietary trends and market projections, with no limits on export of UK agricultural commodities
9	Human diet trend to 2050 – with export limits	Livestock numbers and crop areas for 2050 based on UK human dietary trends and market projections, but with limits to the quantities of UK agricultural commodities exported
10	Tax on meat and dairy/promote fruits and vegetables – 2030	A 20% tax on all meat and dairy consumed in the UK, plus a 20% subsidy on the price of fruits and vegetables
11	Increased meat and dairy alternatives – 2030	Based on the results of discrete choice experiments (DCEs), a 30% switch away from meat and dairy and towards plant-based alternatives was modelled. The switch was assumed only to take place among those already consuming meat and/or dairy
12	Tax on meat and dairy/promote fruits and vegetables – 2050	A 20% tax on all meat and dairy consumed in the UK, plus a 20% subsidy on the price of fruits and vegetables
13	Increased meat and dairy alternatives – 2050	Based on the results of DCEs, a 30% switch away from meat and dairy and towards plant-based alternatives was modelled. The switch was assumed only to take place among those already consuming meat and/or dairy
14	Medium-ambition combination – 2030	Lower emissions from farms, medium ambition, combined with tax on meat and dairy/promote fruits and vegetables
15	High-ambition combination – 2030	Lower emissions from farms, high ambition, combined with increased meat and dairy alternatives

The higher ambition scenario (scenario 5) broadly mapped to the Net Zero pathway as published by the Committee on Climate Change in their Sixth Carbon Budget Report,[25] particularly in terms of agronomic and livestock efficiency gains and reductions in food waste. In addition, there was implementation of higher efficiency (more costly) livestock housing measures and greater use of higher reduction efficiency measures for land spreading. Specifically, the scenario included, in addition to those measures already implemented under scenario 4:

- seventy per cent of slurry/digestate to be applied by shallow (or deep) injection on grass (and arable) and the remaining 30% applied by trailing shoe/hose
- higher uptake (70%) of low-protein diet in the cattle sector

- replace 'grooved floor' as the mitigation option for dairy (slurry) housing with 'in-house acidification', giving emission reductions at housing, storage and spreading
- include 'in-house acidification' for 30% of pig slurry housing (replace 'Acid scrubbers' option where necessary)
- implement washing down dairy cow collecting yards at 80% across all DAs
- implement poultry manure heap covers at 95% across all DAs
- reduce food waste by 20% by 2030 (2025 target from Waste and Resources Action Programme 2017): giving estimates of reduction in associated UK production of 12%, 3.5% and 1.5% of horticultural area, milling wheat area and meat/milk production, respectively
- reduce nitrogen fertiliser use by 15% through improved agronomy, use of legumes and improved accounting for manure nutrients.

TABLE 2 Mitigation measure implementation rates for 2030 in scenario 4 (medium ambition)[24]

| Measure | Applicability | Uptake rate (% of animals/manure, *not* % of holdings) | | | |
		England	Wales	Scotland	N Ireland
Urease inhibitors	Urea fertiliser only (not urea-ammonium nitrate, ammonium nitrate)	100	100	100	100
Rapid incorporation (within 12 hours) of Farm Yard Manure (FYM) applied to arable soils	Dairy, beef and pig FYM applied to arable land. Assumes incorporation method is the same as the existing mix (plough, disc and tine)	70	Slurry 20; FYM 70	70	No change
Rapid incorporation (within 12 hours) of poultry manure applied to arable soils	Assumes incorporation method is the same as the existing mix (plough, disc and tine)	80	80	80	No change
Low emission slurry spreading to grassland	Small amount (about 5%) by shallow injection; remainder by trailing shoe	70	70	70	95[a]
Low emission slurry spreading to arable soils	Small amount (about 10%) by injection; remainder by trailing hose	70	70	70	95[b]
Spreading of digestate	Low emission spreading giving 30% reduction	95	95	95	95
Slurry store covers – above ground tanks	Rigid covers applied to tanks	100	100	100	30
Slurry store covers – earth-banked lagoons	Floating covers applied to lagoons	100	100	100	30
Cover manure field heaps	Sheeting cover on field heaps of manure	–	Poultry 95; cattle and pigs 5	–	–
Digestate store covers	Rigid covers applied to digestate tanks; 95% emission abatement	100	100	100	50
Washing dairy collecting yards	Dairy cattle associated with outdoor collecting yards	80	50	80	15
Acid air scrubbers	Livestock housing for intensive pig and poultry housing	20	50	20	10
Grooved flooring for dairy cattle housing	Applicable to new build	25	25	25	25
Low-protein diets – dairy	Dairy only; assume that pig and poultry already close to ideal	30	30	30	30

a 5% by shallow injection, 45% by trailing shoe, 45% by trailing hose.
b 10% by injection, 85% by trailing hose.
Note
NB: For slurry to arable, maximum uptake (i.e. 70% or 95%) is total across all methods, including incorporation options (which were maintained as in scenario 3).

Modelling the impact of human dietary scenarios on the UK agriculture sector

The human dietary change scenarios, described in *Changing diets for health and the environment*, were assumed to have a direct impact on UK production of different agricultural commodities, and, therefore, the size and make-up of the agricultural sector. Scenarios 6–9 provide BAU forecasts for the agriculture sector based on estimated UK population growth, dietary trends and market trends projected to 2030 and 2050, with (scenarios 7 and 9) or without (scenarios 6 and 8) an assumption regarding limits to exports from the UK. Scenarios 6 and 8 provide the 2030 and 2050 baselines, respectively, against which the impact of the human diet intervention measures were assessed (scenarios 10–13).

Each of these scenarios (10–13) provided estimated changes in UK production from the 2019 base, accounting for population and consumption changes, in cereals, vegetable oils, fruits and vegetables, pulses, potatoes, sugar, dairy products, eggs, beef, lamb, pork and poultry meat. These were then translated into changes in livestock numbers and crop areas (and associated nitrogen fertiliser use). Although provided on a DA basis, changes were applied at the UK level as we cannot assume all DA consumption is produced in that DA. The exception was for grass area and forage associated with changes in grazing livestock numbers, where forage provision can predominantly be expected to be locally grown.

Dairy cow numbers were scaled according to the changes in milk production, accounting for the UKAMM-projected increase in per-cow milk yield. Dairy followers (young animals being kept to replace dairy cows) were assumed to change in direct proportion to dairy cows. There is an interaction between the dairy and beef sectors, in that a proportion of beef finishing animals derive from the surplus calves in the dairy sector. This was considered when scaling beef animals against beef production estimates, assuming that 50% of dairy calves go to the beef sector. A reduction in dairy cow numbers would therefore have to be offset by an increase in beef suckler cow numbers (and associated followers) for a given level of production. Sheep and pig numbers were scaled directly to lamb and pork production. Laying hen numbers were scaled to estimated changes in egg production and all other poultry to estimated changes in poultry meat production.

Areas for specific crops (e.g. potatoes, sugar beet, fruits and vegetables) were scaled directly to estimated changes in production. Grassland and forage crops were scaled according to the estimated changes in grazing livestock (dairy, beef and sheep). Cereal crops (not differentiating between barley, oats and wheat) were scaled initially to estimated changes in cereal production for human food requirement and then further adjusted to the changes in the different livestock categories and the assumed UK cereal area requirement per animal for each of those (based on Audsley *et al.*).[26]

Combination scenarios

Two final scenarios were developed (scenarios 14 and 15) representing medium- and high-ambition combinations of the agricultural and human dietary intervention measures. Using scenario 6 as the base, the medium-ambition agricultural measures (see *Table 1*) and the effects of the meat tax and fruit/vegetable subsidy interventions (see *Dietary scenarios*) were included in scenario 14, and the high-ambition agricultural measures and effects of the encouragement of increased meat and dairy alternatives (see *Dietary scenarios*) were included in scenario 15.

Changing diets for health and the environment

Dietary data

Data summarising current UK diets were obtained from the Family Food module of the Living Costs and Food Survey (DEFRA, 2020),[27] an annual survey of ~5000 households in the UK. The Family Food module records self-report quantities of all food and drink purchases using a 14-day diary, which is then supplemented by till receipts of all purchases, including those made while eating outside the home.

For this study, we used annual summary time series data of average estimated consumption per person from 2001 to 2002, the first year of the Family Food module, up to 2018–9 (the most recent year available). For each year, we aggregated 228 individual food items into 19 food and drink groups: cereals, vegetable oils, fruit, vegetables,

pulses, potatoes, nuts and seeds, foods high in fat sugar and salt, dairy, eggs, beef, lamb, pork, poultry, fish, dairy and meat alternatives, soft drinks, alcoholic drinks, coffee, tea and cocoa drinks (as described in the publication on this study).[24] Fruits and vegetables in processed foods, such as soups and sauces, and fruit juices were not included. The dairy and meat alternative category included non-dairy milks, soy and other novel protein foods. Processed meat and meat in composite dishes were disaggregated and incorporated into the four meat production categories. Dairy products included milk, yogurt, cheese, cream and butter. All foods were expressed as grams per person per day, and we used the quantities purchased as a proxy for consumption. Estimated consumption was calculated in this way for the UK population on average and separately for the lowest quintile of equivalised household income (EHI), a measure of income that takes into account the size and composition of the household (DEFRA, 2020).[27]

Dietary scenarios

We modelled three of the selected AMPHoRA scenarios to the year 2030 (see *Table 1*) and compared food consumption in each scenario against the baseline year of 2019 (the most recent year of data available from the Family Food Survey). These were:

- Scenario 7: Human diet trend to 2030 – with export limits
- Scenario 10: Tax on meat and dairy/promote fruits and vegetables – 2030
- Scenario 11: Increased meat and dairy alternatives – 2030

Based on past trends from 2001 to 2019, we forecast trajectories for consumption of all 19 food and drink groups from 2020 to 2030 in the absence of any new policy interventions (scenario 7). This was done by fitting a range of autoregressive integrated moving average[28-30] models as well as linear regression models. The final model was selected according to the Bayesian information criterion and Akaike information criterion. The best performing model was a random walk model (0,1,0), and so this was adopted for all food groups. This model incorporates one level of differentiation, I(1) and no autoregressive AR(0), or moving average MA(0) elements.

The 'Tax on meat and dairy/promote fruits and vegetables' scenario (scenario 10) proposed a 20% increase in the price of all meat and dairy to account for their environmental, climate, biodiversity and health costs[31] and an equivalent decrease in the price of fruits and vegetables. A subsidy of 20% was recommended by World Health Organization[32] based on strong evidence that subsidies for fresh fruits and vegetables that reduce prices by 10–30% are effective in increasing consumption. There is also evidence that taxes higher than 20% on beverages and foods are more likely to positively impact health behaviours compared to lower tax rates.[33] Food consumption in 2030 according to the human diet trends scenario was used as the baseline, to which the tax scenario was applied. To calculate the change in meat, dairy and fruit and vegetable consumption as a consequence of changed prices, we used UK-specific price elasticities estimated by DEFRA using 2009 Family Food data.[34] Further details of the type of price elasticities and the formula used are given in the supplementary materials to Pastorino *et al.*[24]

The 'Increased meat and dairy alternatives' scenario (scenario 11) modelled the substitution of traditionally produced meat and dairy with more sustainable alternatives: plant-based meat (meat analogues) and dairy and animal proteins produced in laboratories (cultured meat or precision fermentation). To estimate the amount of farmed animal meat that would be substituted with either meat analogues or cultured meat, we used estimates of market share from published discrete choice experiment (DCE) studies.[35,36] Choice experiments present individuals with hypothetical choices between foods or meals under varying assumptions, which may be related to price, sustainability or other factors. The results of such studies can then be used to estimate the potential market share of plant-based meat analogues and laboratory-produced animal protein if these were comparable in price and taste to farmed animal meat. We multiplied consumption in 2030 under current trends by the proportional reduction in meat and dairy according to the market share reported in the DCEs; to aid accuracy, we excluded individuals who stated in the study that they already did not consume meat and dairy. We assumed that meat and dairy would be substituted with the ingredients making up meat and dairy alternatives according to current market availability and future predictions. Further details about the innovation model method are given in the supplementary materials to Pastorino *et al.*[24]

All scenario analyses were conducted using the statistical software Stata 17 (StataCorp LP, College Station, TX, USA). We also conducted Monte Carlo simulation to quantify uncertainties around the central estimates of future food consumption. Input parameters for the estimates under current trends were obtained from autoregressive integrated moving average forecast standard errors. As no error measures were available for the price elasticities calculated from DEFRA to use in scenario 10, we used the average variability for own- and cross-price elasticities from a recent paper that used home-scan data to calculate elasticities for purchases in Great Britain.[37] For scenario 11, we assumed an average 20% variability around market shares, as no error estimate was available for these parameters. All input parameters were assumed to be normally distributed. The simulation model was implemented in Microsoft Excel® (Microsoft Corporation, Redmond, WA, USA), and each scenario was run 10,000 times.

Nutritional targets for dietary scenarios

Based on the NHS Eat well guidance (www.nhs.uk/live-well/eat-well/), we defined targets for healthy consumption of red and processed meat (upper limit) and fruits and vegetables (lower limit). Fruit and vegetable intake should be at least 400 g per person per day, equivalent to five portions a day; this includes fresh, canned, dried and frozen fruits and vegetables, up to one portion of pulses and a maximum of 150 ml of pure fruit juice or smoothies. Red and processed meat should be no more than 70 g per person per day. Red meat includes beef, lamb and pork; processed meat includes meat that has been preserved by smoking, curing, salting or adding preservatives, such as sausages, bacon, ham and salami. These recommendations were chosen because of their relevance to both health and environmental outcomes and because this paper focuses on meat reduction policies with an emphasis on replacement with fruits and vegetables. We defined targets for healthy consumption of red and processed meat (upper limit) and fruits and vegetables (lower limit). Fruit and vegetable intake should be at least 400 g per person per day, equivalent to five portions a day; this includes fresh, canned, dried and frozen fruits and vegetables, up to one portion of pulses and a maximum of 150 ml of pure fruit juice or smoothies. Red and processed meat should be no more than 70 g per person per day. Red meat includes beef, lamb and pork; processed meat includes meat that has been preserved by smoking, curing, salting or adding preservatives, such as sausages, bacon, ham and salami. These recommendations were chosen because of their relevance to both health and environmental outcomes and because this paper focuses on meat reduction policies with an emphasis on replacement with fruits and vegetables.

Environmental footprints of dietary scenarios

We calculated GHG emissions and water use for the whole diet per person per day for the baseline in 2019 and all scenarios using values adapted from Poore and Nemecek's review of global environmental footprints.[38] First, we aggregated the Family Food data on individual foods into 54 food groups so that these could be mapped onto the foods in the Poore and Nemecek paper, and then we aggregated the footprints further into the 19 groups used for the rest of the analysis on the basis of weighted average consumption. For meat, we calculated the weighted meat content of processed meats (which frequently have other ingredients such as cereals added).

Next, we applied factors for GHG emissions and water footprints as stated in the Poore and Nemecek data set, using country-specific footprints where these were available. Where country-specific footprints were not available, we used the global average. To calculate the correct impact of each food, we included information on whether the food was imported or produced in the UK. The following equation was used to allocate GHG and water footprint values depending on the imported amount:

$$I_f = (Consumption) * ((1 - Import) * National\, I) + (Consumption * Import * Global\, I) \qquad (1)$$

where: I = impact (GHG emissions in $kgCO_{2e}$/kg; water use in l/kg); f = food group; Consumption is kilograms per day per person; Imports are percentage of imported food; Global refers to average environmental footprint across all countries for which an estimate is provided excluding UK; National refers to UK-specific environmental footprints.

Greenhouse gas emissions were aggregated into global warming potential in carbon dioxide equivalents (CO_{2e}) using Intergovernmental Panel on Climate Change (2013) characterisation factors with climate-carbon feedbacks. Water use was calculated as the freshwater withdrawals related to food consumption, which includes irrigation water, animal drinking water, and water used during food processing. The 54 food groups and their environmental footprints can be found in the supplementary materials of Pastorino et al.[24]

Atmospheric modelling

Spatially resolved emission scenario estimates

Agricultural census/survey data for 2019 (baseline year) were acquired at the holding level from the country statistics authorities in the UK – that is, DEFRA (England), the Scottish Government (Scotland), Welsh Government (Wales) and Department of Agriculture, Environment and Rural Affairs (Northern Ireland). Aggregated cattle population data were supplied by Cranfield University from cattle tracing system data. The holding-level data for the different countries were aggregated to a common set of emission source categories used by the SMT to ensure compatibility between the UK countries.

For 2030 emission scenarios, holding-level livestock numbers and crop areas were scaled evenly across each of the UK countries to forecast totals (taken from SMT output).

Agricultural emissions were estimated using the SMT, separately for each of the UK countries and emission source. As with the UK agricultural emission inventory, detailed emission source strength estimates were derived for the main livestock emission components (housing, manure storage, yarding, land spreading of manures, grazing) for the individual emission source categories. Average fertiliser N application rates to different crops and types of grassland were taken from the British Survey of Fertiliser Practice for 2019 (BSFP 2020).[39]

Average emission factors were then applied in the Atmospheric Emissions for National Environmental Impacts Determination (AENEID) model (e.g. Dragosits *et al.* 1998),[40] using the original holding-level data to derive high-resolution 1 km × 1 km grid resolution emission surfaces. The area-based non-disclosive distribution methodology works by identifying and merging civil parishes which contain fewer than five holdings. Within these (merged) parish areas, emissions were then distributed to suitable land cover types, using an updated version of the original AENEID methodology by Dragosits *et al.* (e.g. arable land, improved grass, part-improved grass, rough grazing, etc.), using the UK Centre for Ecology & Hydrology (UKCEH) Land Cover Map for the year 2015 (i.e. Land Cover Map 2015, Rowland *et al.*, 2017).[41]

These 1 km × 1 km grid resolution emission estimates were then formatted for inclusion into the European Monitoring and Evaluation Programme for the UK (EMEP4UK) model, which was run at a grid resolution of ≈3 km x ≈3 km.

European Monitoring and Evaluation Programme for the UK model

The EMEP4UK is a Eulerian atmospheric chemistry and transport model which simulates the emissions, transport, chemical transformations and deposition of a wide range of pollutants and provides hourly outputs.[42,43] The EMEP4UK model was used to model the atmospheric chemistry for a base run and 14 different NH_3 emission scenarios. Meteorological input data were created with the Weather Research Forecast model version 4.2.2 for the year 2019. EMEP4UK was based on EMEP model version rv4.36 and run at a resolution of 3×3 km^2 over the British Isles, nested within a European domain with a horizontal resolution of 27×27 km^2. For the EMEP4UK input emission, the 2018 National Atmospheric Emissions Inventory (NAEI, https://naei.energysecurity.gov.uk/) at 1×1 km^2 resolution were used for the UK domain and the 2018 EMEP v2020 (Centre on Emission Inventories and Projections, www.ceip.at/) 0.1×0.1 degrees emissions for the European Union. The 2019 forest fires are also included in the model. The NAEI is used for a 10 km buffer around the UK coast, and the remaining shipping emissions are derived from the EMEP emissions. The base run consists of 2018 emissions, meteorological year 2019 and 2019 forest fires. For the scenarios, only NH_3 was perturbated, and all other emissions and parameters remained the same as the base run.

Systematic scoping review of the health literature

A systematic search of the literature was performed to identify studies linking exposure to agricultural-derived air pollution and defined clinical outcomes [i.e. using *International Classification of Diseases* (ICD) codes]. This was performed according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, where possible, within the remits of a scoping review. We searched MEDical Literature Analysis and Retrieval System, Excerpta Medica

dataBASE, and Cochrane Review databases for studies evaluating the association between agricultural air pollution and adverse health outcomes in adults and children. The list of search terms used is available in *Appendix 1*. We included all studies, systematic reviews and meta-analysis from database inception to 24 March 2021 (ongoing research is updating this search to 2023). Studies were included if they were published in peer-reviewed journals, with no restrictions placed on study age. Additional studies were identified through manual review of bibliographic reference lists in the studies selected for inclusion in full-text review. This study was registered with PROSPERO CRD42020172116.

Quantification of impact on health

Building on previous work (e.g. Milner *et al.*, 2015; Milner *et al.*, 2023; Karakas *et al.*, 2023; Eustachio Colombo *et al.*, 2021),[18,44–46] we developed and applied a novel health impact assessment method combining both mortality and morbidity to quantify the potential health effects associated with changes in air pollution exposure and diets under each agricultural and dietary scenario. The model uses a life table approach based on adaptation of the existing IOMLIFET model (Institute of Occupational Medicine, Edinburgh, UK).[47] The life table models the pattern of survival in a population over age and time, based on age-specific mortality rates that are adjusted to reflect changes in mortality risk under each scenario. Morbidity (disease incidence) calculations were then performed on the output population from the life table.

We quantified the health impact of five scenarios:

- Current market trend to 2030 (BAU)
- Lower emissions from farms – high ambition 2030
- Tax on meat and dairy/promote fruits and vegetables – 2030
- Increased meat and dairy alternatives – 2030
- High-ambition combination – 2030 (lower emissions from farms, combined with increased meat and dairy alternatives).

Figure 1 summarises the structure of the AMPHoRA health model.
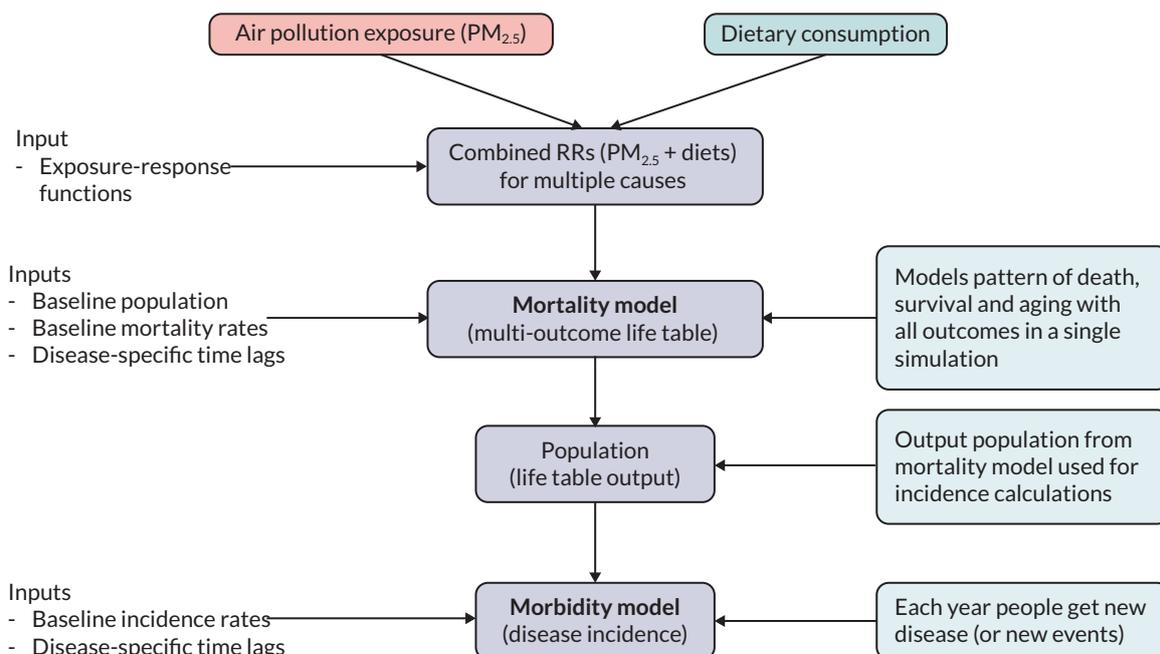
FIGURE 1 Assessing Mitigation Pathways to Realise Public Health Benefits of Air Pollutant Emission Reductions from Agriculture (AMPHoRA) health model structure. RRs, relative risks.

Population exposures

Air pollution

To generate input $PM_{2.5}$ exposure data for the health model, the scenario-based annual average concentrations of $PM_{2.5}$ (*Figure 2*) modelled at 3 × 3 km resolution by WP2 (see *Atmospheric modelling*) were overlaid with population-weighted centroid of the smallest areal boundary that population statistics are available (2020 population at Output Area for England and Wales, 2020 population at Small Area for Northern Ireland and 2020 population at Data Zone for Scotland) and Index of Multiple Deprivation, Income domain (2019 at Lower level of Super Output Area for England and Wales, 2020 at Data Zone for Scotland and 2017 at Super Output Area for Northern Ireland). For our health modelling, population subgroups for air pollution exposure were set according to the available food consumption data, that is, by sex, age group (0–9, 10–14, 15–19, 20–64, 65 years and over), nation (England, Wales, Scotland and Northern Ireland) and income deprivation quintile (1–5, where 1 is the most deprived). To represent each population subgroup's long-term $PM_{2.5}$ exposure level, the population-weighted average of $PM_{2.5}$ annual mean concentration was calculated for each of these subgroups. *Figure 3* shows summary statistics of population-weighted $PM_{2.5}$ annual mean concentration among these population subgroups (2 sex groups × age 5 groups × deprivation 5 groups × 10 region/countries) by regions/countries and income deprivation groups.

Food consumption

Consumption of fruits, vegetables, legumes, nuts, whole grains, milk, red meat, processed meat and sugar-sweetened beverages (SSBs) under each scenario was estimated using the methods described in *Changing diets for health and the environment*.

Average daily consumption data (g/d) from the dietary scenarios were available for EHI quintiles but not for gender and age strata. To obtain estimates of consumption broken down by EHI, gender and age, we used data from the National Diet and Nutrition Survey to scale the available average intakes to different gender and age categories. These intake estimates were then used to estimate impact for different strata: male and female, further subdivided by EHI (5 quintiles) and age (25–65, 66 + years). Dietary consumption was assumed to be the same for all nations, as intakes by nation for all different strata were not available in National Diet and Nutrition Survey.

PM₂.₅ annual mean
Based on AI1_2030 (S4) by 3 x 3 km

Output area (pop-weighted centroid)
+ Income deprivation index 2019 (LSOA)

Weighted by sex-age-income-region specific population 2020
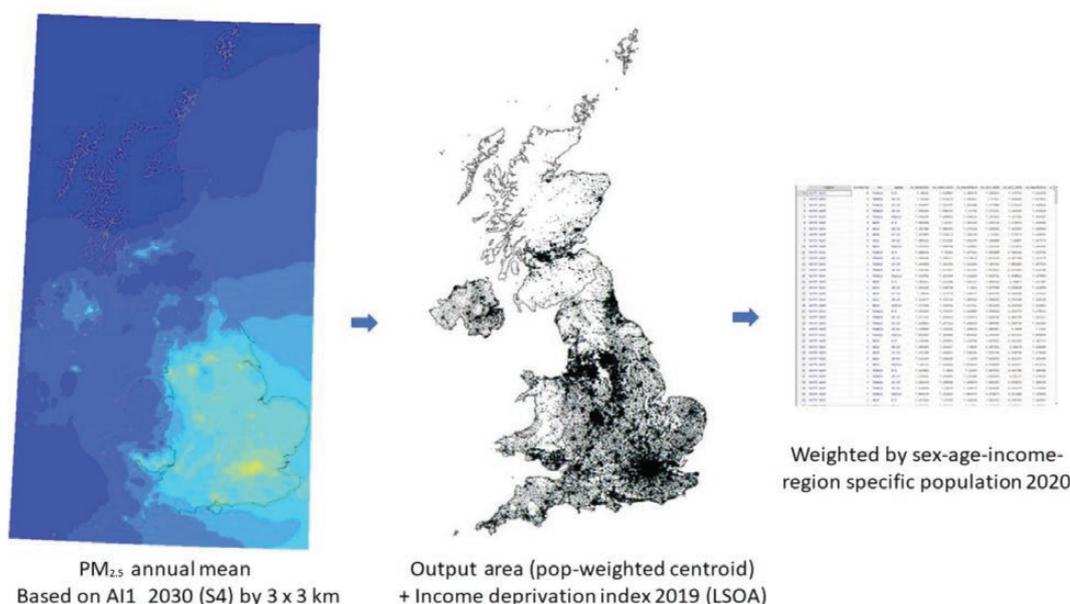
FIGURE 2 $PM_{2.5}$ annual mean concentration based on scenarios by 3 × 3 km and population-weighted centroid of the small area (Output Area in England and Wales, Data Zone in Scotland and Small Area in Northern Ireland). LSOA, lower-layer super output area.
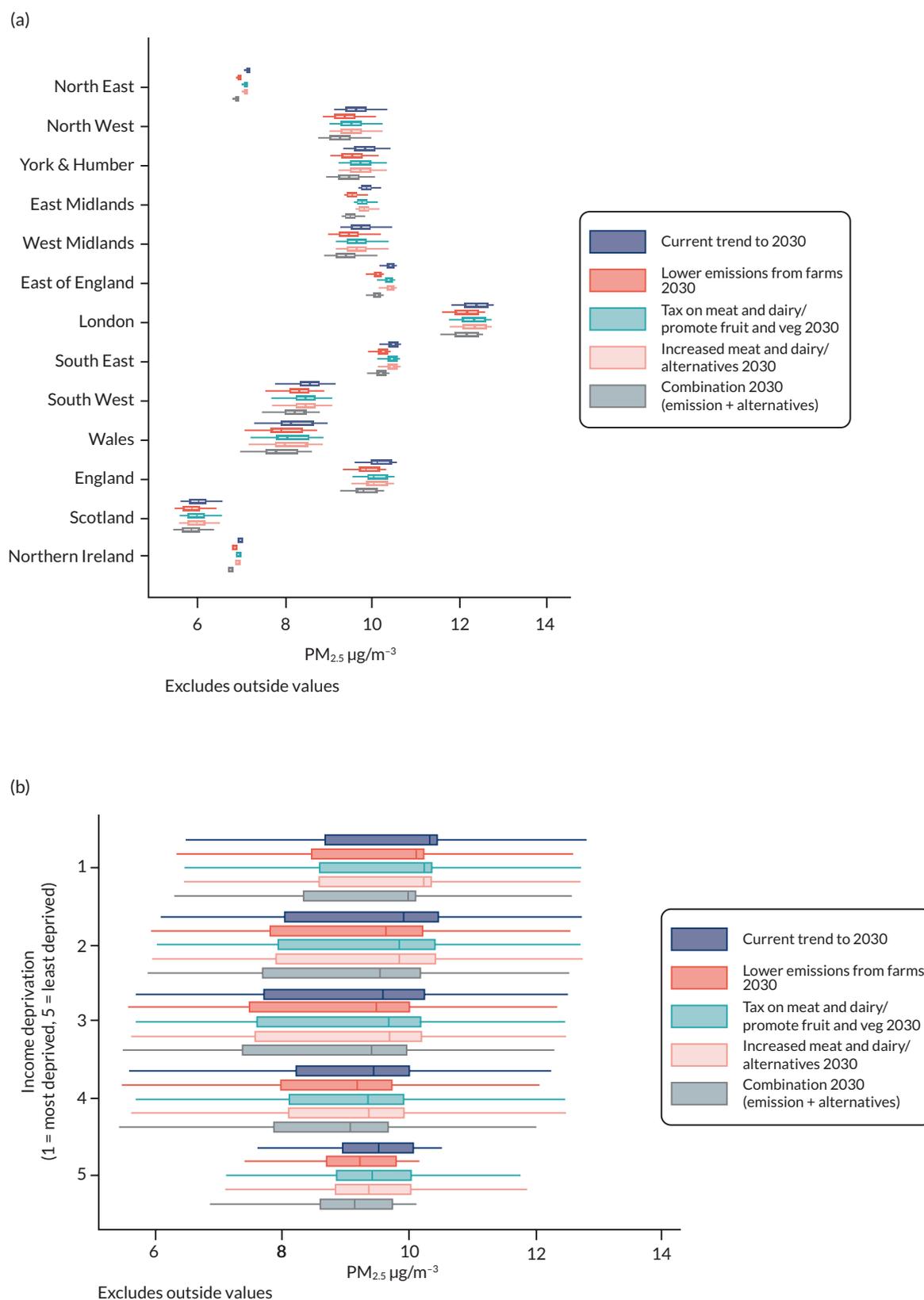
FIGURE 3 Summary statistics (including median, 25th and 75th percentile) of annual mean PM$_{2.5}$ concentration of population subgroups by regions/countries (a) and income deprivation (b), where 1 is the most deprived and 5 is the least deprived group.

Quantification of impact on mortality

We used age-specific population data and age- and cause-specific mortality data for the year 2019 available from the GBD study (GBD 2019 Disease and Injuries Collaborators, 2020)[48] to set up separate life tables for males and females and for each of the four nations of the UK (England, Scotland, Wales and Northern Ireland) to reflect their different underlying mortality rates. *Table 3* shows the disease outcomes included in the life table models and their *International Statistical Classification of Diseases and Related Health Problems*, Tenth Revision (ICD-10) codes. The disease-specific mortality data were only available by 5-year age groups and not in single-year-of-age format. Using the weighted mean age of the UK population in each interval, the mortality rate for each 1-year age interval was interpolated with monotonic cubic spline functions using the programme SRS splines, available as an add-in to Microsoft Excel [Srs1 Software LLC. *SRS1 cubic spline for Microsoft Excel v2.5 for Windows*. (Software) Boston, MA, USA: Srs1 Software LLC. 2015].

To approximate differences in mortality rates by socioeconomic status, we further subdivided each of the life table models into five equally sized populations to represent quintiles of income deprivation (1–5, where 1 is the lowest income) and adjusted the cause-specific mortality rates in each group using ratios of mortality rates in different socioeconomic groups using measures of multiple deprivation for the year 2019 [Office for National Statistics (ONS) 2021a; ONS 2021b; ONS 2021c; National Records of Scotland, 2020][49–52] (2 genders × 4 nations × 5 income deprivation quintiles = 40 models per scenario).

To quantify the effect of changes in $PM_{2.5}$ exposure and dietary consumption on cause-specific mortality, we calculated and applied relative risks (RRs) for each scenario using exposure-response functions from the 2019 GBD study (*Table 4*). For $PM_{2.5}$, we used the GBD's meta-regression–Bayesian regularized trimmed (MRBRT) non-linear risk curves for six health outcomes – lung cancer, ischaemic heart disease (IHD), stroke, lower respiratory infection (LRI) and chronic obstructive pulmonary disease (COPD). The MRBRT curves are based on analysis of epidemiological evidence from global studies of long-term exposure to household air pollution and ambient air pollution. We applied the curves to calculate changes in mortality risk at age 25 and above. For cardiovascular diseases (IHD, stroke), unique MRBRT curves were used at 5-year age intervals to account for evidence suggesting that the RR decreases with age.

For diets, we modelled the exposure-outcome pathways shown in *Table 4* based on changes in consumption of fruits, vegetables, legumes, nuts, whole grains, milk, red and processed meat and SSBs on breast cancer, colorectal cancer, oesophageal cancer, prostate cancer (PC), lung cancer, type 2 diabetes mellitus (T2DM), IHD and stroke. All dietary RR estimates are based on the most recent GBD systematic reviews of evidence and, where possible, are adjusted for

TABLE 3 Modelled disease outcomes and ICD-10 codes

Health outcome	ICD-10 underlying cause of death classification
IHD	I20 – I25.9
Ischaemic stroke	G45–G46.8, I65–I66.9, I67.0–I67.3, I67.5–I67.6, I68.1–I68.2, I69.0–I69.3
Haemorrhagic stroke	Cerebrovascular diseases (I60–I63)
COPD	Chronic lower respiratory diseases (J40–J47)
LRIs	Influenza and pneumonia (09–J18) Other acute LRIs (J20–J22)
Tracheal, bronchus and lung cancer	C33–C34.9, D02.1–D02.3, D14.2–D14.3, D38.1
Oesophageal cancer	C15–C15.9, D00.1, D13.0
Colorectal cancer	C18–C21.9, D01.0–D01.3, D12–D12.9, D37.3–D37.5
PC	C61
Breast cancer	C50–C50
Type 2 diabetes mellitus (T2DM)	E11–E11.1, E11.3–E11.9

TABLE 4 Summary of 2019 GBD exposure-outcome pathways for air pollution and dietary exposures

Risk factor	Health outcomes	RR changes with age
Air pollution		
Ambient PM$_{2.5}$	Lung cancer	No
	T2DM	No
	LRIs	No
	COPD	No
	IHD	Yes
	Stroke (all)	Yes
Diets		
Diet low in fruits	Oesophageal cancer	No
	Tracheal, bronchus and lung cancer	Yes
	IHD	Yes
	Ischaemic stroke	Yes
	Intracerebral haemorrhage	Yes
	Subarachnoid haemorrhage	Yes
	T2DM	Yes
Diet low in vegetables	Oesophageal cancer	No
	IHD	Yes
	Ischaemic stroke	Yes
	Intracerebral haemorrhage	Yes
	Subarachnoid haemorrhage	Yes
Diet low in whole grains	Colon and rectum cancer	No
	IHD	Yes
	Ischaemic stroke	Yes
	T2DM	Yes
Diet low in nuts and seeds	IHD	Yes
	T2DM	Yes
Diet low in milk	Colon and rectum cancer	No
Diet high in red meat	Breast cancer	No
	Colon and rectum cancer	No
	IHD	Yes
	Ischaemic stroke	Yes
	Intracerebral haemorrhage	Yes
	Subarachnoid haemorrhage	Yes
	T2DM	Yes
Diet high in processed meat	Colon and rectum cancer	No
	IHD	Yes
Diet high in legumes	IHD	Yes

known confounders, including body mass index so that risk from diet could be separated from risk from obesity. The curves were again applied at age 25 and above. Where exposures ($PM_{2.5}$ and/or dietary exposures) affected the same disease outcome, we multiplied the RRs to account for potential double counting of impacts.

We applied cause-specific time lag functions based on cumulative distribution functions of normally distributed variables (S-shaped curves) from the first year of each scenario to account for delays between changes in exposure and changes in mortality risk. These functions, which we have used in previous modelling analyses,[18,44,53] are based on evidence on the effect of smoking cessation on mortality over time,[54] the effects of dietary interventions on various causes of mortality over time[55-58] and plausible assumptions about disease progression (*Figure 4*).

All exposure changes under the scenarios were assumed to be instantaneous (i.e. to occur in the first year of the scenario), and underlying mortality rates were assumed to remain constant for the duration of follow-up. The life tables were evaluated over a period of 106 years, representing a time long enough for the initial population (maximum age 105 years) to be extinguished. The main outcomes from the life tables were annual population, deaths and life-years (LYs) lived by age and calendar year under each scenario.

Quantification of impact on morbidity

The age- and year-specific population structures outputted from the life tables for each scenario were used as the underlying populations for calculations of disease incidence for each outcome shown in *Table 4*. We applied age-specific GBD 2019 incidence rates to the output life table population and applied the same GBD exposure-response functions for $PM_{2.5}$ and dietary consumption as described above for mortality. The GBD incidence data represents both the number of new cases of disease per year and the occurrence of new events in the population. The incidence data were interpolated to single-year-of-age using the same monotonic cubic spline method as used for mortality rates, and adjusted to account for differences by income using the same method as described above. The same time lag functions were also applied to the incidence calculations.

The main outputs from the combined mortality-morbidity model were annual changes in LYs and cause-specific deaths and disease incidence per year compared to the BAU scenario in which current trends are assumed to continue until 2030.
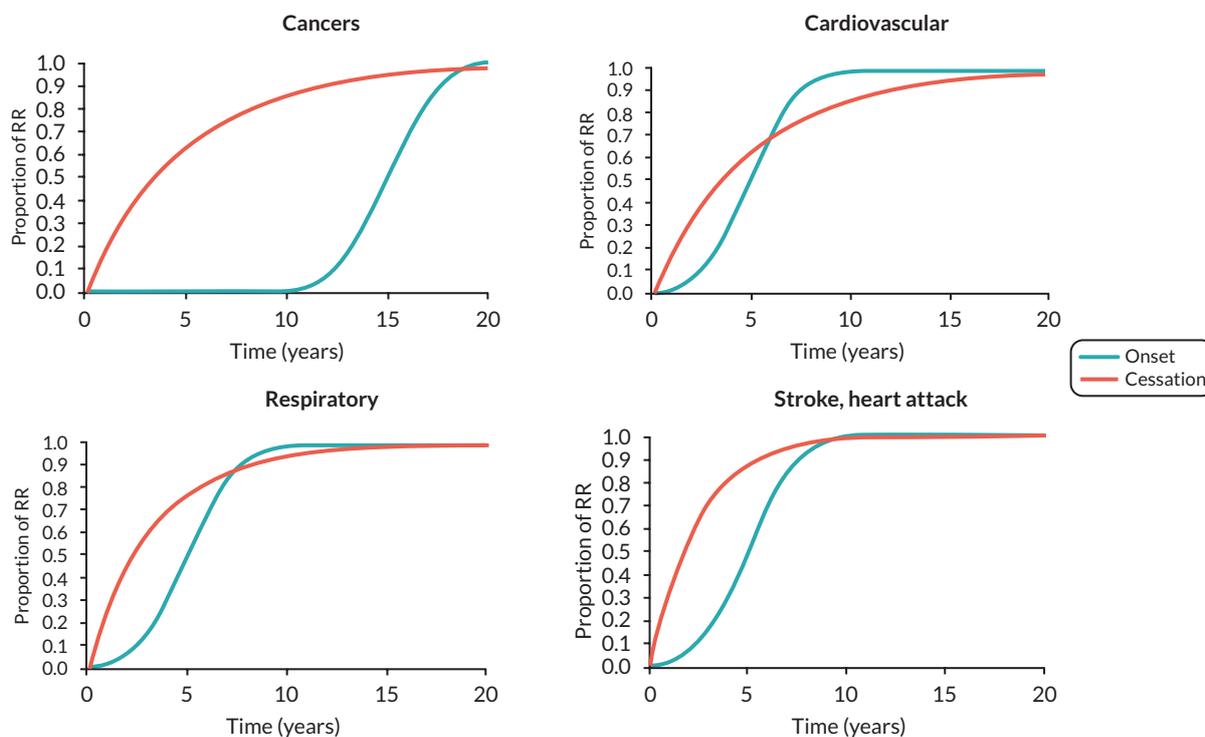
FIGURE 4 Onset (blue) and cessation post-onset (red) time lag functions used in the health modelling analysis.

Comparing scenarios

Overview of methods for comparative analysis

Three methods have been investigated for the comparison of outcomes of the scenarios involving further action (agricultural measures and/or fiscal measures) against the baseline scenario:

- Cost-effectiveness analysis (CEA): CEA seeks to identify the measures that are most economically efficient for attaining the objectives of analysis. For the present study, these objectives could be defined in terms of the quantity of NH_3 emission reduced or health outcomes.[59]
- Cost–benefit analysis (CBA): CBA compares monetised costs of measures with monetised benefits, to the extent that health and other benefits can be monetised. By making a direct comparison of costs and benefits, CBA provides an answer to the question of whether something is worth doing or not.[60]
- Multi-criteria decision analysis (MCDA): MCDA is used to establish preferences between options by reference to an explicit set of objectives. Rather than using money as the 'common currency' for this comparison, MCDA develops scores for each effect, and these scores can be weighted according to their perceived importance. The weighting process is conventionally done through consultation with stakeholders, though other options are possible.[61]
- Evaluation of the uncertainties in results, to consider the extent to which conclusions drawn could be affected by uncertainty and to define priorities for further research based on the principles of valuation of information.

The analysis carried out at this stage of the work picks up the outputs from previous stages as described above, for example, changes in emissions of NH_3, changes in health outcomes and the estimated cost of measures to reduce emissions. Further details on the methods and values used are given in *Appendix 2* (*Tables 13–24*).

Cost-effectiveness analysis

Cost-effectiveness analysis has been used here to assess the efficiency of different technical measures for reducing emissions of NH_3. Measures were ranked according to their cost per unit of NH_3 emission abated.

Key outputs from the CEA concern:

- The ordering of measures in terms of cost per unit emission abated.
- How much emission (if any) can be saved using measures with costs per unit emission estimated to be negative, for example, as a result of efficiency savings.
- How much emissions can be reduced by overall by the measures identified.

While these outputs are useful, the limitations of CEA need to be recognised. The results of CEA do not indicate whether action is merited, as they simply differentiate measures against a reduction in pollutant emissions with no indication of the value of those emission savings. What they provide, instead, is an indication of the most efficient route to attaining specific policy goals: in this case, a reduction in emissions of NH_3 without taking account of wider impacts of measures, such as their effect on GHG emissions. To do that requires impacts to be expressed on a consistent basis, done here through the use of CBA, where effects are expressed uniformly in economic terms. A second limitation arises from an assumption that the measures included in a cost curve provide a complete description of potential for emission control. However, the measures included are limited to those for which data on costs and effectiveness are available. Behavioural measures, in particular, tend to be omitted from cost curves as it is often difficult to obtain data on their costs for a given level of effectiveness. In our analysis, CEA did not include the dietary measures as a full accounting of the costs associated with dietary change, notably the consequences for the agricultural sector, was not possible.

However, as long as these limitations are recognised, the use of CEA enables a logical structuring of many measures and hence provides insight on efficient policy options.

Cost–benefit analysis

In order to carry out CBA, it is necessary to monetise the impacts (here focused primarily on health) associated with the reduction in NH_3 emissions and dietary change. Health valuation considers health and other care costs, lost productivity and lost utility (freedom from pain and suffering, and the ability to undertake activities as one chooses).

The costs of health care and productivity are available from published sources using data available from the NHS. Costs of impacts on utility are based on information from surveys regarding quality of life for different conditions and public preference for allocation of resources to protect health. For the analysis carried out here, account also needs to be taken of effects of NH_3 on ecosystems and of GHG emissions. Full discussion of the derivation and sources of the values adopted here, summarised in *Table 5*, is presented in *Appendix 2*.

Key outputs from the CBA concern:

- Whether quantifiable benefits of action exceed costs or of action or not.
- The extent to which benefits exceed costs, expressed through the benefit-to-cost ratio. The higher this ratio, the more efficient measures or strategies are at reaching desired goals.

Like CEA, CBA also has limitations that need to be recognised. A particular issue concerns the completeness of accounting of costs and benefits. For the health benefits of reduced air pollution, this may be especially important, recognising the expansion of impacts recognised as being linked to pollution in recent years as at least partially reflected in the methods used in this report.

Multi-criteria decision analysis
The use of MCDA was considered to enable impacts that are not monetised to be factored into a decision-analytic framework. The following key issues were identified where the approach could add benefit:

- affordability of interventions on farms for the UK farming industry
- impacts of dietary change on the UK farming industry
- additional health impacts of air pollution and dietary change that are not covered by AMPHoRA
- assessment of ecological impacts (monetised, but with high uncertainty).

TABLE 5 Valuation data for the CBA

Condition	Care costs	Productivity	Utility	Total
Health impacts (£ per new incidence of disease)				
Lung cancer	38,000	370,300	39,600	447,900
Bowel cancer	53,700	191,200	18,900	263,800
Breast cancer	54,900	76,800	27,600	159,300
Other cancers	50,800	214,500	21,500	286,800
COPD	17,800	10,200	51,900	79,900
Stroke	222,500	13,200	210,000	445,700
Type 2 diabetes	16,900	14,500	222,000	253,400
IHD	10,300	18,200	250,000	278,500
LRIs	211	Not assessed	370	581
LYs lost	–	–	52,000	52,000
Non-health impacts (£ per tonne of pollutant)				
Ecosystem impacts of NH_3				487
GHG emissions (per tonne CO_{2e})				See *Appendix 2*, *Table 23*
Note For sources and so forth, see *Appendix 2*. All values in £, price year 2022.				

However, following review of the data gathered in the research, a formal appraisal via MCDA was not considered likely to generate informative conclusions given the current state of data on these impacts. In the case of effects of dietary change, for example, a range of outcomes are possible for farms depending on various factors, such as:

- Whether farms continue production at current levels despite reduced UK demand for certain goods, through increasing exports. This depends on, among other things, the existence or lack of barriers to export.
- How the UK public respond to changes in food prices. This depends on numerous factors, including knowledge of cooking a reduced meat/milk diet, the willingness of the UK population to change, other pressures on budgets as highlighted through the current cost of living crisis and so on.

A further factor concerned the inevitable subjectivity of the weighting process used in MCDA.

These issues are each research projects in their own right. It was considered most useful to provide a structured discussion of issues arising, rather than to formalise analysis via MCDA in a way that may appear to make it more robust than it really is. This does not rule out the use of MCDA in this area in the future.

Uncertainty analysis

So far as the CEA and CBA carried out in AMPHoRA is concerned, the purpose of uncertainty analysis is focused on whether uncertainties both in what is quantified and what is not could affect the conclusions reached on the relative benefits of different courses of action (e.g. continuing BAU or applying various controls or interventions). Consideration has been given in the study to using ranges around key parameters (response functions, valuations, etc.), to the use of sensitivity analysis around key parameters and discussion of unquantified factors ('biases').

Value of information analysis can be used particularly to highlight the areas of future research that are most likely to improve the quality of analysis or permit assessment to encompass a broader range of factors. The approach as applied here has been used to consider what additional knowledge would most help to refine the results of the assessment.

Chapter 3 Results

Mitigation options for emissions from agriculture

Impact of current (2019) implementation of mitigation measures

Ammonia emissions from UK agriculture in 2019, as reported in the 2021 national inventory submission, were 239 kt. Of this, emissions from cattle accounted for 48% (28% from the dairy sector and 20% from the beef sector), poultry for 15% and pigs for 8%. Emissions from nitrogen fertiliser applications accounted for 24%. By removing all implemented mitigation measures (scenario 2), it was estimated that current implementation of mitigation measures by the UK agriculture sector reduces total NH_3 emissions by 33 kt (12% of the unmitigated total). This was primarily through the implementation of measures to reduce emissions from manure application to land, but also some (assumed) uptake of measures for manure storage and livestock housing by permitted pig and poultry farms under the Industrial Emissions Directive.

Current trends emission projections

There were differences in the projections of livestock numbers and crop areas for 2030 as given by the UKAMM model (scenario 3) and those based on the trends in human dietary consumption, population growth and agricultural commodity export trends (scenario 6). The UKAMM model forecast a reduction in beef cattle and poultry numbers, with a small increase in dairy, whereas the projected dietary trends resulted in a much greater reduction in dairy cattle numbers, but an increase in beef cattle (due to human population growth and increased export, despite per capita reduction in consumption – see more detail in *Changing diets for health and the environment* and *Changing diets for health and the environment*) and in laying hen numbers (*Figure 5*). These changes in the underlying activity data obviously resulted in changes in the estimated BAU emission projections for 2030. There is a small (3%) increase in emissions from the 2019 base scenario to the 2030 projection based on the UKAMM forecast (*Figure 6*). Projections based on the human dietary trends to 2030 and 2050 (scenarios 6 and 8) give larger increases in emission compared to 2019, of 8% and 5%, respectively. In the scenarios in which a limit is included on exports (scenarios 7 and 9), increases to 2030 and 2050 are slightly less, at 6% and 2%, respectively. There are also differences in the relative importance of the different sources between the projections, with beef and poultry being greater under the dietary trends scenarios, while dairy is greater under the UKAMM scenario. All projection scenarios are subject to great uncertainty, but it is important to acknowledge the differences in the two approaches taken here and to use the appropriate base for assessment of effect of further intervention scenarios; that is, scenario 3 is the base for comparison against the agricultural intervention scenarios 4 and 5, while scenarios 6 and 8 (without export limits) were used as the base for comparison against the human diet intervention scenarios 10 and 11 for 2030 and 12 and 13 for 2050, respectively. Scenario 6 was also the basis for comparison against the combination scenarios 14 and 15.

Agricultural interventions

The medium- and high-ambition scenarios for reducing farm emissions (scenarios 4 and 5) gave emission reductions at the UK scale of 14% and 26%, respectively, compared with the 'Current market trend to 2030' scenario (scenario 3), with respective emission reductions of 33 kt and 63 kt NH_3 (*Figure 7*). Largest emission reductions are associated with the changes to nitrogen fertiliser use, particularly for the higher ambition scenario, where efficiency measures mean a significant overall reduction in fertiliser requirement. The dairy sector has the next largest proportional reduction in emissions, again particularly under the higher ambition scenario, where higher efficiency measures targeted at housing and outdoor yards are introduced. However, the relatively modest emission reductions under both scenarios highlight the difficulty (and unfeasibility) of implementing technical measures across the large number of often-diffuse emissions sources that exist within the agricultural sector.

Human dietary interventions and combined scenarios

The impact of the interventions to change human diet on consumption patterns is detailed in *Changing diets for health and the environment*. The impact that this subsequently has on the size and make-up of the UK agricultural sector, and hence NH_3 emissions, is shown in *Figure 8*. Compared against the projections for 2030 and 2050 based on human dietary trends (with no limits to exports of UK Agricultural commodities), the meat tax and vegetable subsidy scenarios (scenarios 10 and 12) gave emission reductions of 14% and 20%, while the increases in consumption of plant-based
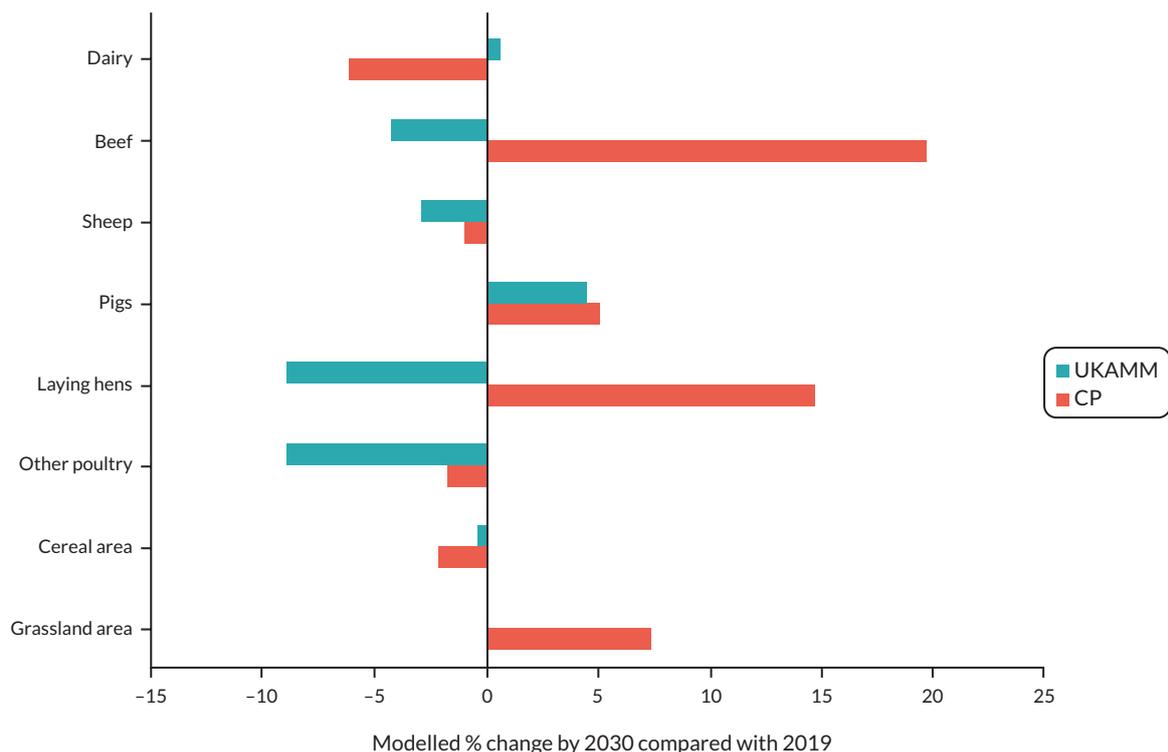
FIGURE 5 Changes in livestock numbers and land area requirement (as a % compared with 2019) under BAU scenarios for 2030 based on DEFRA UK Agricultural Market Model projections (UKAMM) and forecast food consumption/production trends (CP).
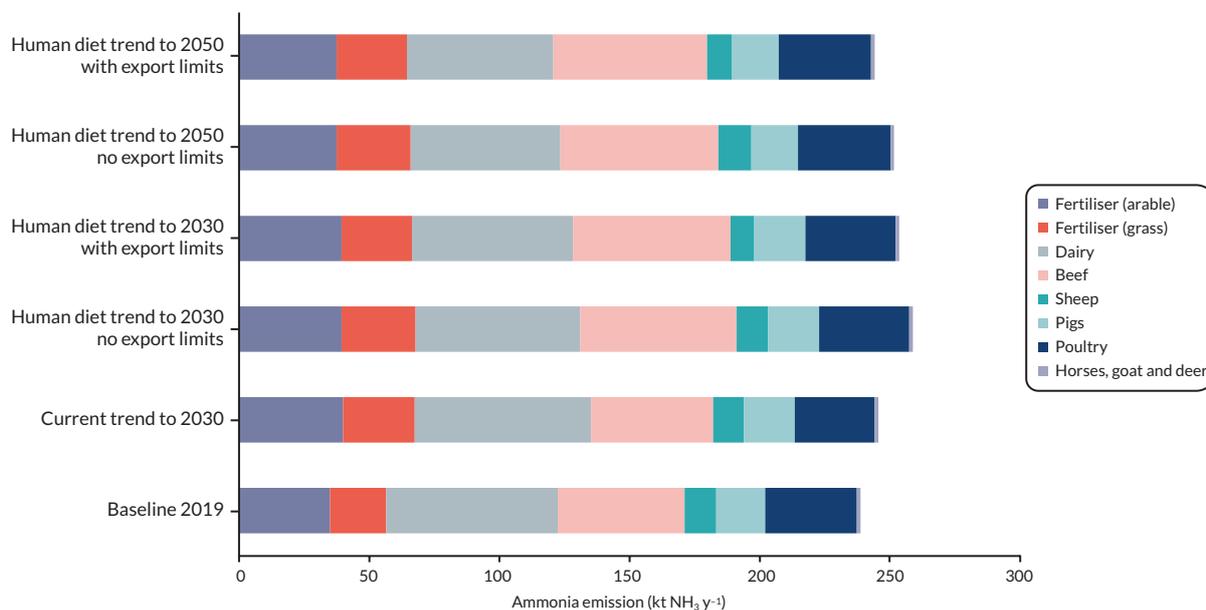
FIGURE 6 United Kingdom agriculture NH_3 emission projections based on current trends in agricultural markets and on human dietary consumption trends.

foods gave emission reductions of 16% and 19% for 2030 and 2050, respectively. As might be expected, emission reductions are across all livestock sectors, and from a reduction in the grassland area (and associated nitrogen fertiliser applications) required for ruminant livestock. However, these reductions are offset to some extent, particularly in the meat and dairy alternatives scenarios, by an increase in the required crop area and associated nitrogen fertiliser applications.
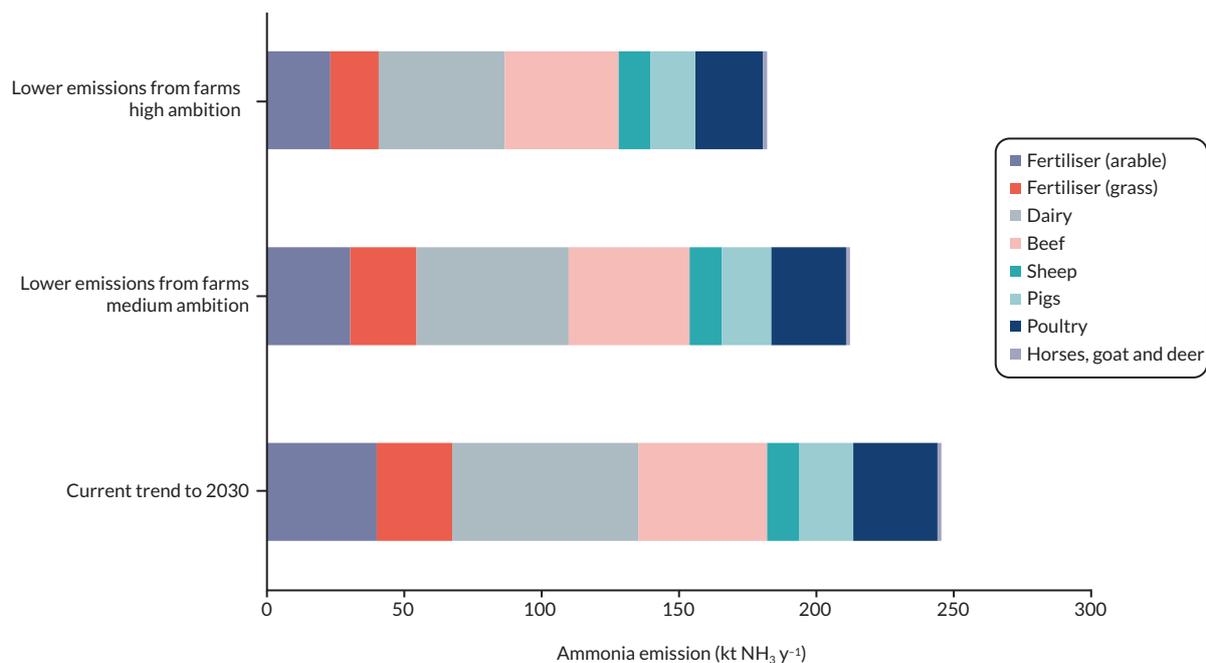
FIGURE 7 Impact of implementing largely technical measures (medium- and high-ambition scenarios) on NH$_3$ emissions from UK agriculture in 2030.
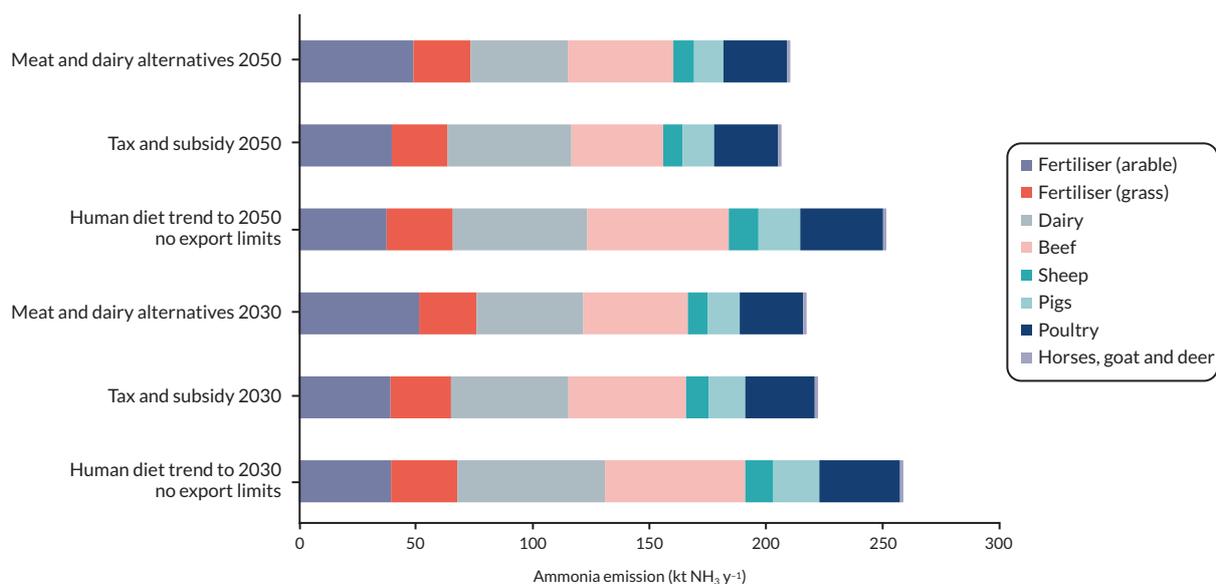
FIGURE 8 Impact of human diet interventions on NH$_3$ emissions from UK agriculture in 2030 and 2050.

Finally, the impacts of combining the implementation of technical measures to reduce emissions from agriculture with interventions to change UK human consumption patterns on NH$_3$ emissions from UK agriculture are shown in *Figure 9*. Including the medium-ambition on-farm mitigation measure implementation with the meat tax and vegetable subsidy scenario gave an emission reduction of 25% against the human diet trend to 2030 (no export limits) base scenario, while including the higher-ambition on-farm mitigation measure implementation with the increase in plant-based foods in the diet gave an emission reduction of 38%. The emission reductions were spread across all the agricultural sectors.
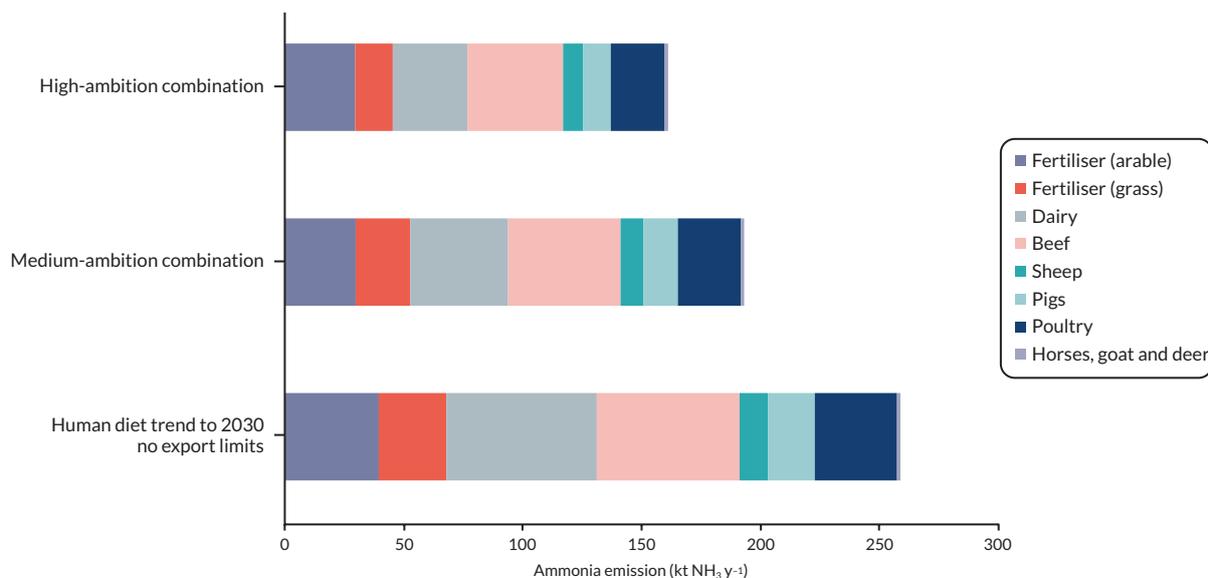
FIGURE 9 Impact of scenarios combining the on-farm and human diet interventions on NH_3 emissions from UK agriculture in 2030.

Changing diets for health and the environment

The three scenarios used for the dietary modelling were scenario 7 (human diet trend to 2030 with export limits), scenario 10 ('Tax on meat and dairy/promote fruits and vegetables') and scenario 11 ('Increased meat and dairy alternatives'). These three scenarios were compared against baseline food consumption in 2019, with a focus on reductions in consumption of meat and dairy and increases in consumption of fruits and vegetables.

Reductions in meat and dairy consumption

Under current dietary trends, consumption of red meat and dairy would be expected to decline by 11% by 2030 in comparison to the baseline in 2019. However, consumption of poultry would increase by 7%, meaning that the overall decline in meat consumption would be more modest (*Figure 10*). This is due to a general trend towards replacement of red meat with poultry in recent years which may partly reflect the reduced cost of poultry.
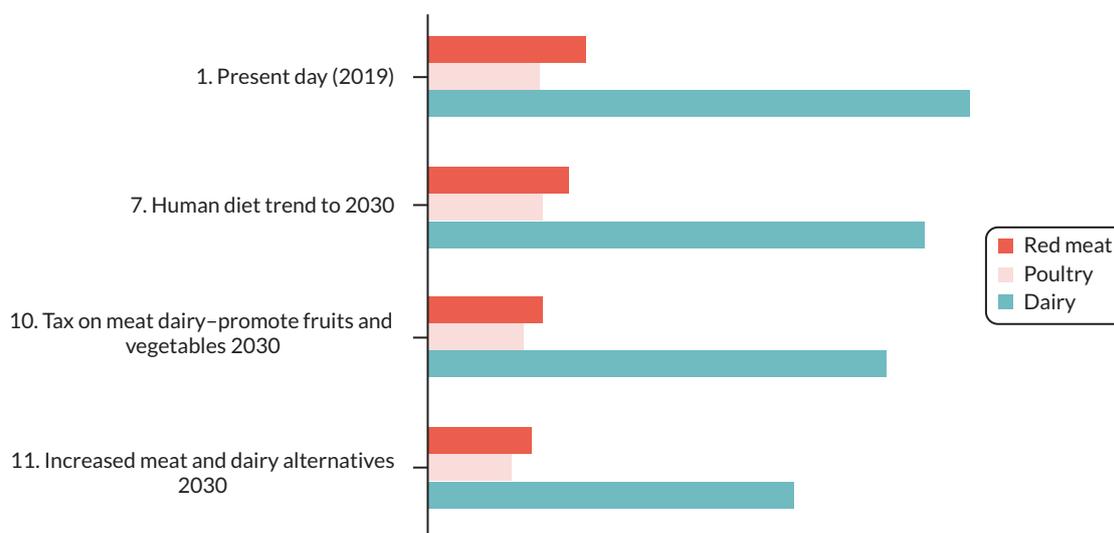
FIGURE 10 Changes in consumption of meat and dairy (g/capita/day) under different policy scenarios in 2030 compared to 2019.

Compared to 2019 levels, under scenario 10, the reductions in red meat and dairy consumption would be greater than those under current trends (a reduction of 27% for red meat and 15% for dairy). Consumption of poultry would also reduce by 14%.

Under scenario 11, consumption of red meat, poultry and dairy would be lowest due to switching away from these foods in favour of plant-based alternatives. Red meat consumption would decline by 35%, poultry consumption by 24% and dairy consumption by 32%.

Increases in consumption of healthy plant-based foods

Based on current trends (scenario 3), there would only be small increases in consumption of fruits and vegetables (by 4% and 3%, respectively) and a small reduction (3%) in consumption of pulses (*Figure 11*).
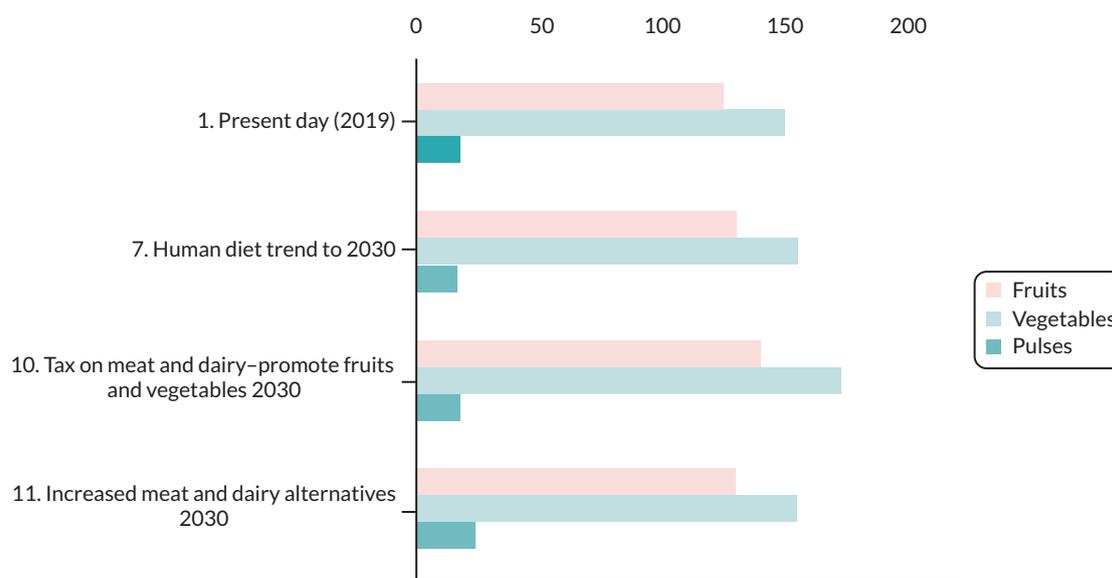
FIGURE 11 Changes in consumption of fruit, vegetables and pulses (g/capita/day) under different policy scenarios in 2030 compared to 2019.

The tax on meat and dairy scenario (scenario 10) would lead to greater increases in consumption of fruits (13%) and vegetables because these foods would be subsidised in price under this scenario. The increase in consumption of pulses would be slightly lower (7%), as pulses were not explicitly included in the subsidy (only fresh fruits and vegetables). However, their consumption would also increase slightly as a consequence of increased price of meat and decreased price of fresh fruits and vegetables (cross-price elasticity).

Under the 'Increased meat and dairy alternatives' scenario (scenario 11), consumption of fruits and vegetables would remain largely static, with a 4% increase in consumption of fruits and a 3% increase in consumption of vegetables compared to the 2019 baseline. However, consumption of pulses would increase by 34% under this scenario due to the high content of pulses in many meat and dairy alternatives, including soy protein, soy milk and lentils.

Meeting targets for nutrition

Despite increases in consumption of fruits, vegetables and pulses, most of the scenarios still did not meet the NHS recommendations for adults to consume at least 400 g (or five portions) of fruits and vegetables per day (*Figure 12*). The 'Tax on meat and dairy/promote fruits and vegetables' scenario (scenario 10) brought average consumption closest to the target at 357 g, with the human diet trend to 2030 scenario (scenario 7) being furthest away at 327 g.

The scenarios suggested a greater degree of success in meeting the target for red and processed meat consumption of a maximum of 70 g/capita/day (*Figure 13*). Both scenarios 10 and 11 brought average consumption below the target (to 62 g and 55 g per day, respectively), although the human diet trend to 2030 (scenario 7) would leave average consumption still above the target.

Grams per person per day
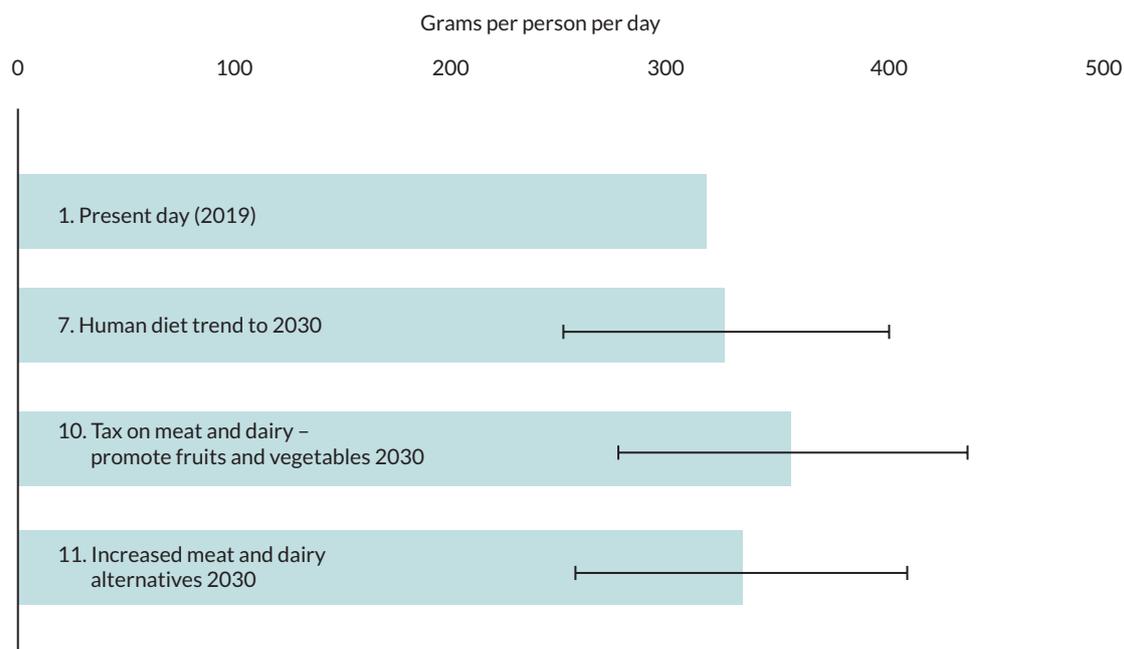
FIGURE 12 Mean [and 95% confidence intervals (CIs)] fruit and vegetable consumption (g/capita/day) under different scenarios in 2030.

Grams per person per day
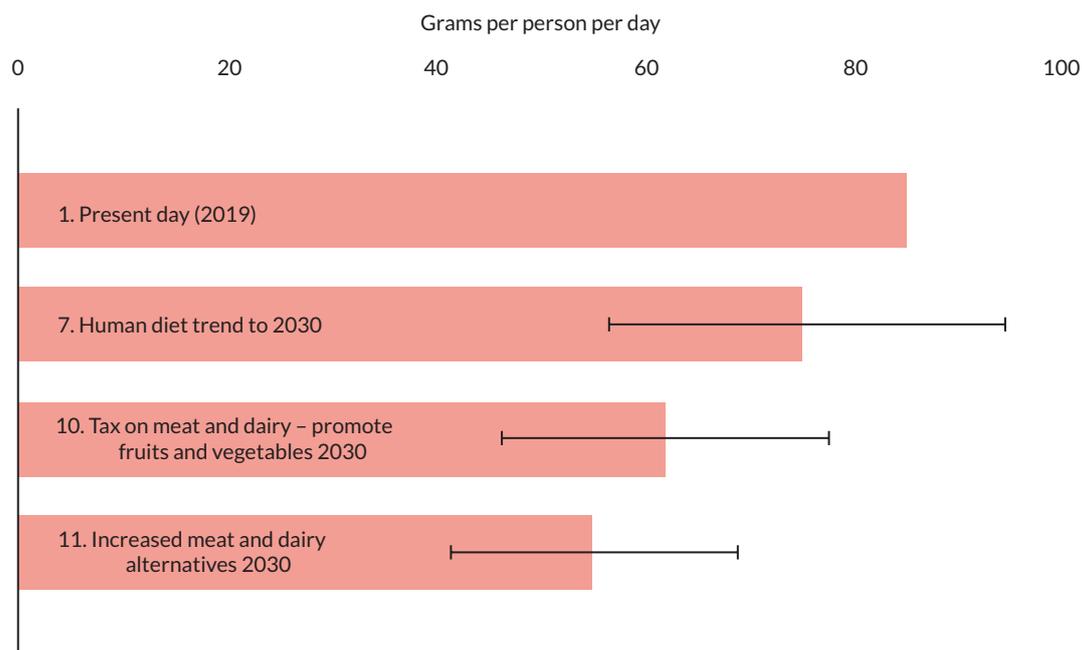
FIGURE 13 Mean [and 95% confidence intervals (CIs)] red and processed meat consumption (g/capita/day) under different scenarios in 2030.

Greenhouse gas emissions and water footprints

Environmental footprints of the average diets were reduced compared to baseline in all scenarios. For GHG emissions, up to a 20% reduction in average emissions was seen in the scenarios, with the 'Increased meat and dairy alternatives – 2030' scenario (scenario 11) having the biggest reduction due to its greater reduction in meat consumption. The 'Tax on meat and dairy/promote fruits and vegetables – 2030' scenario (scenario 10) also achieved a substantial reduction in emissions of 16% compared to the 2019 baseline, while the human diet trend to 2030 scenario (scenario 7) would achieve an 8% reduction.

Reductions in water use were slightly lower than for GHG emissions, but the 'Increased meat and dairy alternatives – 2030' scenario demonstrated a 16% reduction in water use, with the 'Tax on meat and dairy/promote fruits and vegetables – 2030' scenario showing a 9% reduction and the human diet trend to 2030 scenario a 3% reduction.

Outcomes for low-income adults

Adults in the lowest quintile for household income had less healthy diets at baseline in 2019, including consuming less fruits and vegetables and more soft drinks. However, they also tended to consume less red meat, and therefore their diets had lower baseline environmental impacts (around 20% lower for GHG emissions compared to the population average, and around 10% lower for water footprints).

Reductions in meat and dairy consumption were projected to be greater under all scenarios for the low-income group, due to larger predicted responses to price changes among this group (*Figure 14*). Consumption was projected almost to meet the Climate Change Committee target of a 20% reduction in the lowest income quintile under current trends, whereas in the whole population the projected reduction was much smaller. Under the 'Tax on meat and dairy/promote fruits and vegetables – 2030' scenario (scenario 10), again adults in the lowest income quintile would meet the 20% reduction target, but the whole population would not meet this target on average. Finally, under the 'Increased meat and dairy alternatives – 2030' scenario (scenario 11), the population average reduction would be > 20%, but the reduction among the lowest income quintile would be proportionally greater.

Increases in fruit and vegetable consumption would also be slightly higher for households in the lowest income quintile, meaning that they would be expected to experience greater health benefits as a result of the meat reduction scenarios. However, consumption would remain below the population average in this group under all scenarios; even in the most beneficial scenario (the 'Tax on meat and dairy/promote fruits and vegetables – 2030' scenario), fruits and vegetables consumption would reach 3.7 portions per day compared with 4.1 portions per day in the population on average.

Modelling changes in air quality

Figure 15 presents the changes in agricultural NH_3 emissions under each scenario relative to the present-day (2019) baseline. Areas in red indicate an increase in agricultural NH_3 emissions relative to the 2019 baseline, with blue areas indicating a decrease. The 'Increased meat and dairy alternatives – 2030' scenario, for example, shows a mix of areas in red, where emissions are higher than present day; and blue, where emissions are lower. Switching to a more plant-based diet would reduce emissions from livestock (because demand decreases) but may also lead to increased fertiliser emissions (as we grow more plant crops for direct human consumption).

Figure 16 presents changes in NH_3 concentrations (primarily driven by changes in NH_3 emissions) under each scenario relative to the present-day (2019) baseline. Areas in red indicate an increase in NH_3 concentrations, relative to
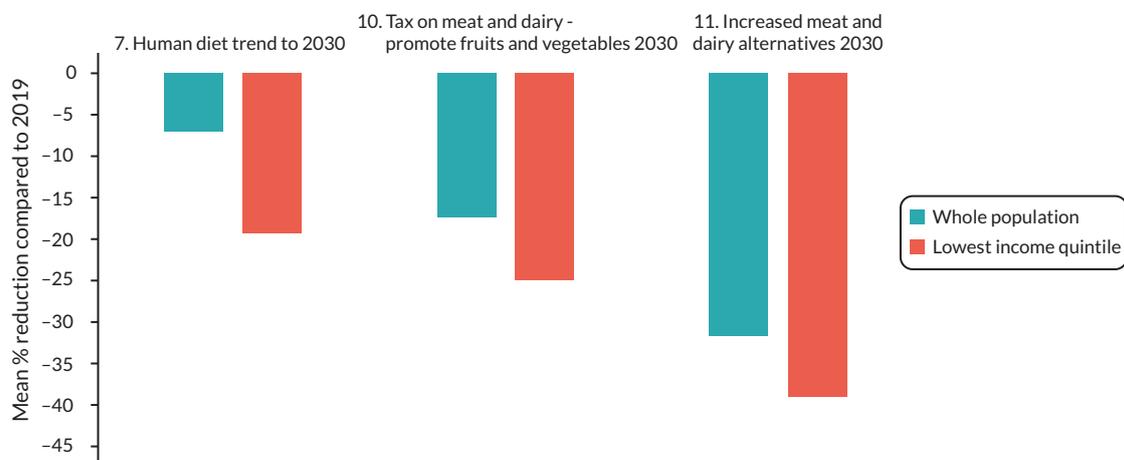
FIGURE 14 Mean percentage reductions in meat and dairy consumption compared to 2019 among whole population and lowest income quintile.
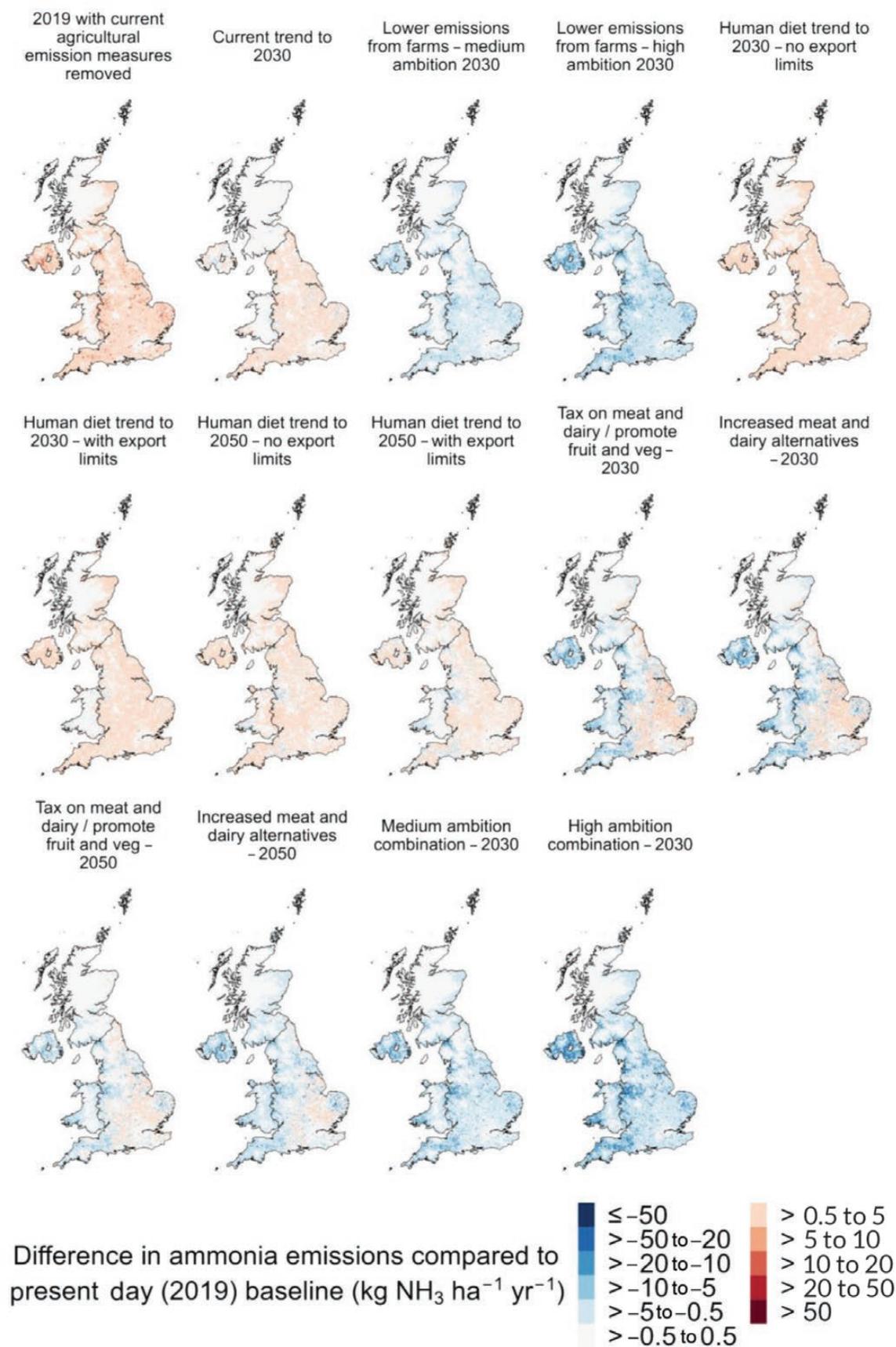
FIGURE 15 Difference in agricultural NH$_3$ emissions under each scenario relative to the present-day (2019) baseline.
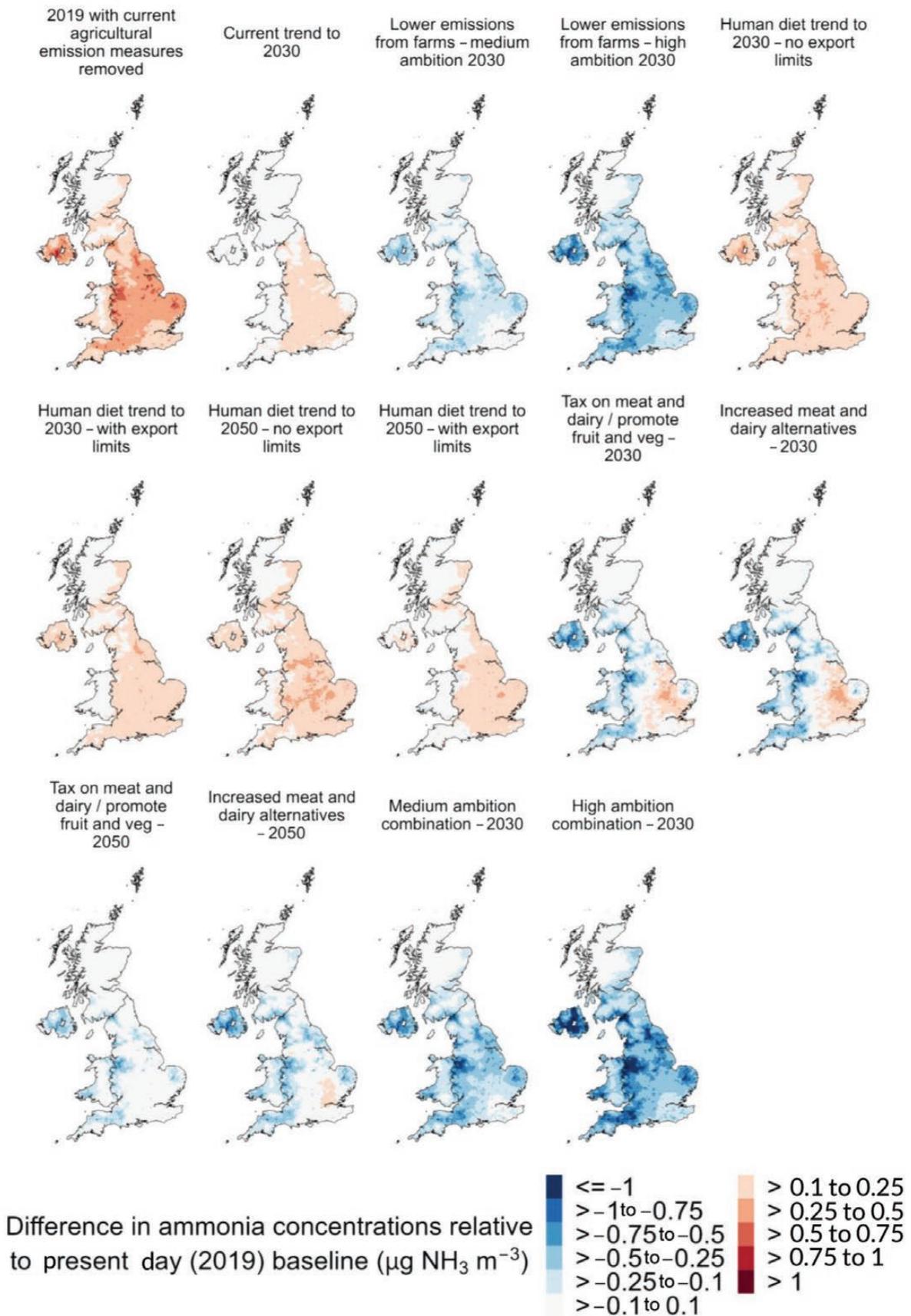
FIGURE 16 Difference in EMEP4UK-modelled NH$_3$ concentrations under each scenario relative to the present-day (2019) baseline.

estimates for 2019 baseline, with blue areas indicating decreases. Areas in the UK dominated by cattle emissions (such as Northern Ireland and Cumbria) tend to be associated with the largest decreases (under most scenarios) relative to 2019. Areas with increased NH_3 concentrations (relative to 2019) are typically associated with increased emissions from fertiliser application (in particular, under the BAU scenarios).

Figure 17 presents changes in $PM_{2.5}$ concentrations modelled under each scenario relative to the present-day (2019) baseline. Differences in $PM_{2.5}$ concentrations follow similar patterns to NH_3 concentrations overall, but they are influenced by other sources. $PM_{2.5}$ is associated with long-range transport, and up to 50% of $PM_{2.5}$ may be imported into the UK (on annual average) from elsewhere.[42] NH_3 from the agricultural sector contributes to the formation of ammonium sulfate and ammonium nitrate; however, the modelled $PM_{2.5}$ also includes sea salt, secondary organic aerosols, biomass burning, dust and primary emission of $PM_{2.5}$. Each component is associated with a specific spatial distribution. After NH_3 is emitted to the atmosphere, it needs to intercept an acid (nitric and sulfuric acid are present in the model), where it will neutralise to form ammonium (either or both ammonium nitrate and ammonium sulfate). These acids may be created at different locations to where NH_3 is emitted. For example, sulfuric acid may be associated with power plants and urban areas. The effect is to decouple the location of the NH_3 emissions with the ammonium aerosol. In addition, the lifetime of ammonium particulate is longer than that of NH_3 gas. This further smooths the formed aerosols compared with the NH_3 gas. The spatial distributions of $PM_{2.5}$, primary $PM_{2.5}$, NH_3, ammonium, ammonium nitrate, sulfate, fine windblown dust, SO_2 and NO_2 for the present-day (2019) baseline are shown in *Figure 18*.

In order to present and visualise the complex data sets developed by AMPHoRA, a prototype data explorer tool was developed and tested with stakeholders in online and in-person workshops. The tool allowed for the interactive exploration and visualisation of AP emissions, ambient concentrations and population exposure data in a spatially explicit fashion based on maps. Health and socioeconomic data resulting from the health impact and CBA can be presented by different pre-set indicators (*Figure 19*).

Systematic scoping review of the literature on agricultural air pollution and human health

Our search identified 7175 studies. After exclusion of duplicate records, 3297 records were screened at abstract level and 62 at full-text level, with 6 articles deemed as relevant for the final analysis (*Figure 20* and *Table 6*). Across 6 studies, 11 objective estimates were provided for the effect of agricultural pollution on respiratory diseases. Estimates for COPD or chronic bronchitis were provided in two studies, asthma in two studies and respiratory infection in two studies. Two studies provided estimates for medication dispensing for obstructive airways disease as a surrogate measure of disease prevalence and severity. The pollutant that was investigated varied across the six studies included in our analysis, with two prospective cohort studies measuring NH_3,[71,69] two cross-sectional studies estimating PM_{10} concentrations from agriculture[72,73] and two considering $PM_{2.5}$.[70,74] Two-thirds (*n* = 4/6) found no link between agricultural pollution and adverse health outcomes. One study found an association between agricultural pollution and death due to IHD, and one an association with an increased likelihood of chronic bronchitis. It was not possible to calculate pooled estimates because of significant heterogeneity in study methodology, including population definition, study design, outcome measures and measure of pollution.

Modelling health impacts from changes in diet and air quality

Here, we report the results from our health impact modelling for selected AMPHoRA intervention scenarios, namely: 'Lower emissions from farms – high ambition 2030' (scenario 5) – note, this is only for NH_3 emissions from farm; 'Tax on meat and dairy/promote fruits and vegetables – 2030' (scenario 10); 'Increased meat and dairy alternatives – 2030' (scenario 11) and 'High-ambition combination – 2030' (scenario 15: scenario 5 combined with scenario 11).

Net effects of scenarios on health
Overall, these four intervention scenarios would result in considerable net benefits for health across the UK in terms of reduced mortality and disease incidence and increased LYs lived by the population. *Figure 21* presents the health impacts over 30 years (i.e. difference between the 'Current market trend to 2030' scenario and each four intervention 2030 scenarios). Of the three individual scenarios (scenarios 5, 10 and 11), in terms of mortality and additional LYs, 'Tax
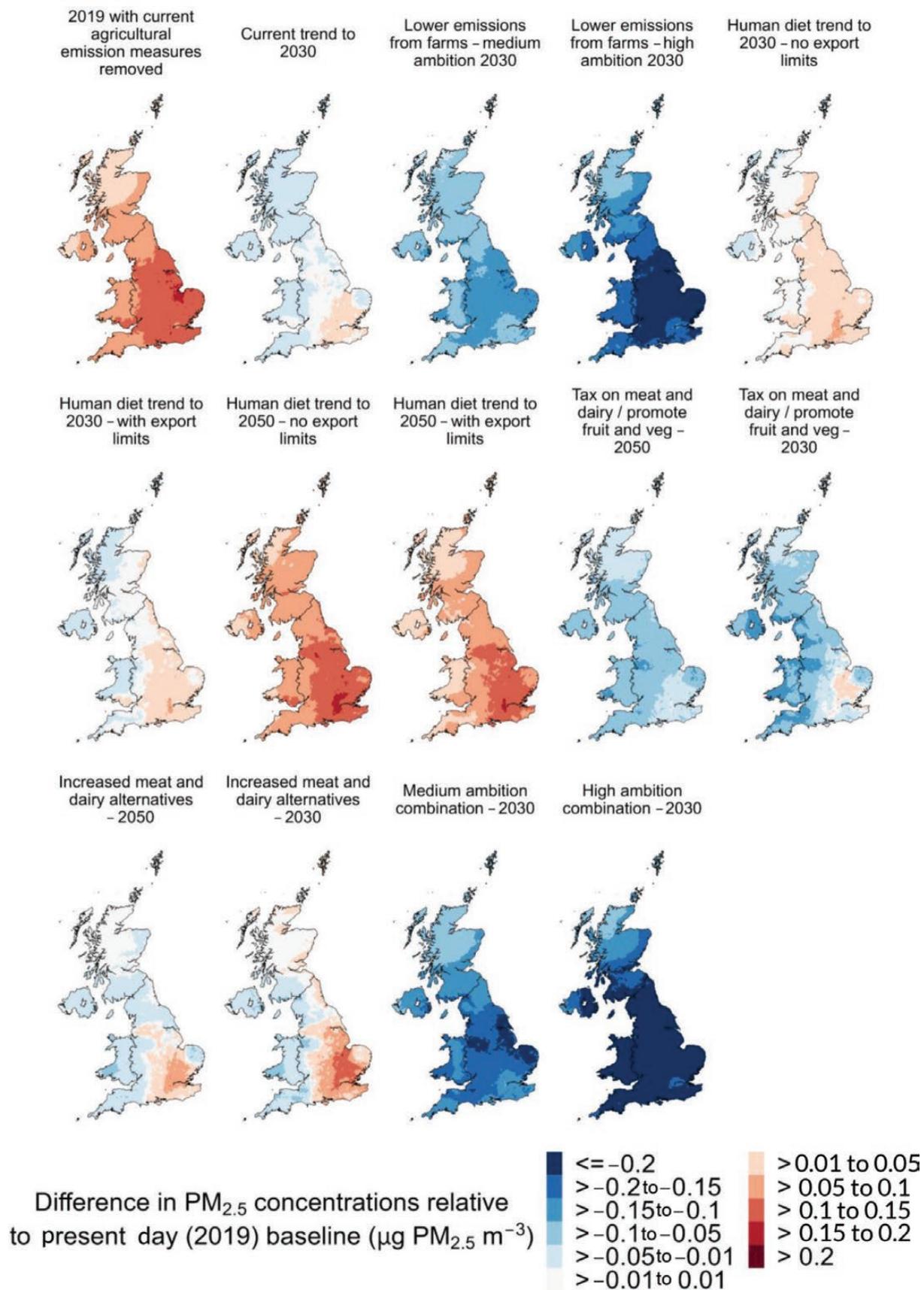
FIGURE 17 Difference in agricultural PM$_{2.5}$ concentrations under each scenario relative to the present-day (2019) baseline.
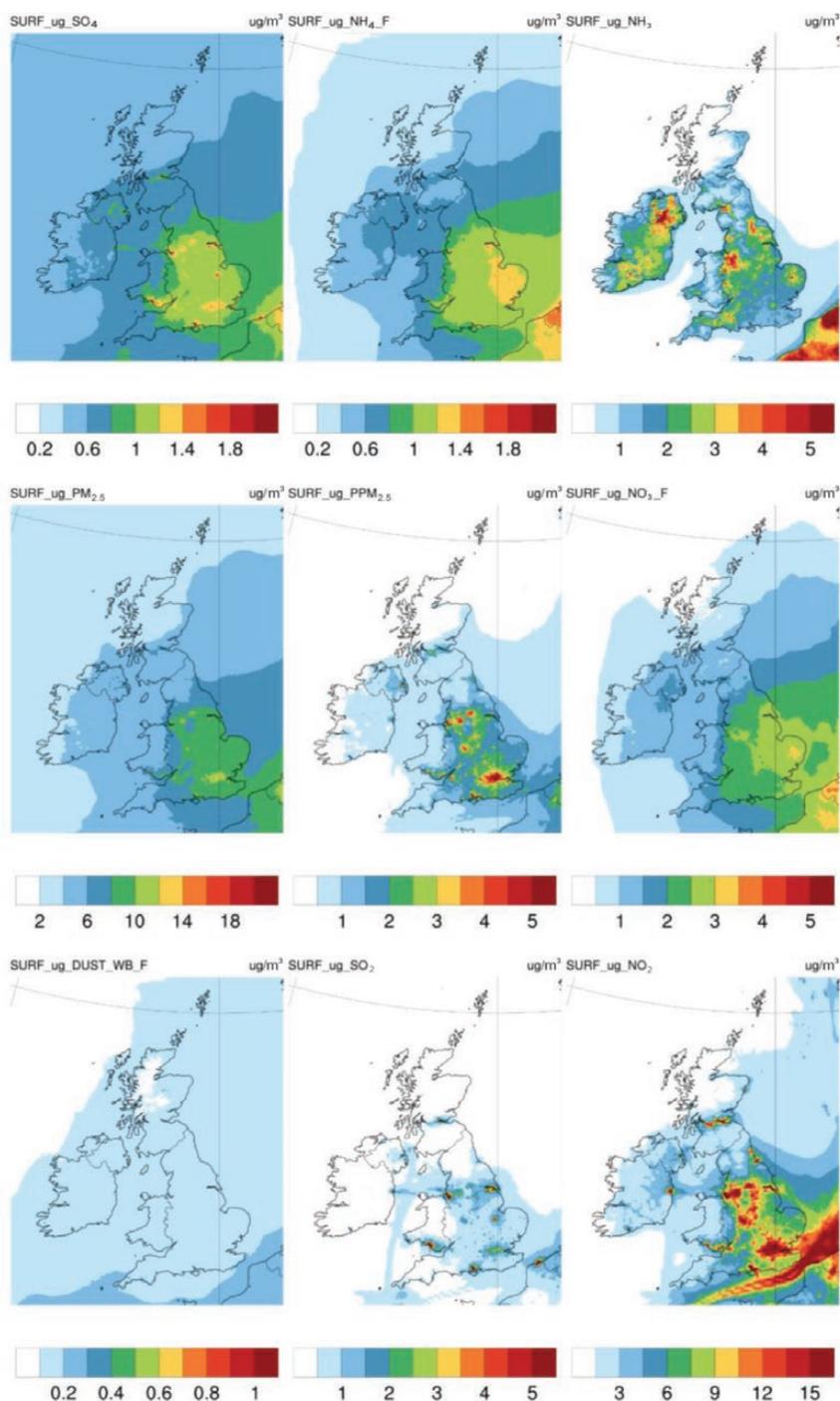
FIGURE 18 Yearly 2019 baseline emissions for surface concentrations of SO_4^{2-} (µg/m³), NH_4^+ fine aerosol (µg/m³), NH_3 (µg/m³), $PM_{2.5}$ (µg/m³), primary $PM_{2.5}$ (µg/m³), NO_3^- fine aerosol (µg/m³), fine windblown dust (µg/m³), SO_2 (µg/m³) and NO_2 (µg/m³).

on meat and dairy/promote fruits and vegetables' (scenario 10) and 'Increased meat and dairy alternatives' (scenario 11), which affect both exposure to $PM_{2.5}$ and dietary patterns in the UK, result in broadly equivalent health benefits (≈65,000 deaths averted and ≈550,000–600,000 LYs gained over 30 years), while the benefit under the 'Lower emissions from farms – high ambition 2030' (scenario 5), which only reduces $PM_{2.5}$ exposure but has no effect on diets (i.e. no changes to dietary patterns), is comparatively smaller, approximately a 10th for aged 0–65 and a quarter for aged 65 +.

How are human health outcomes affected?
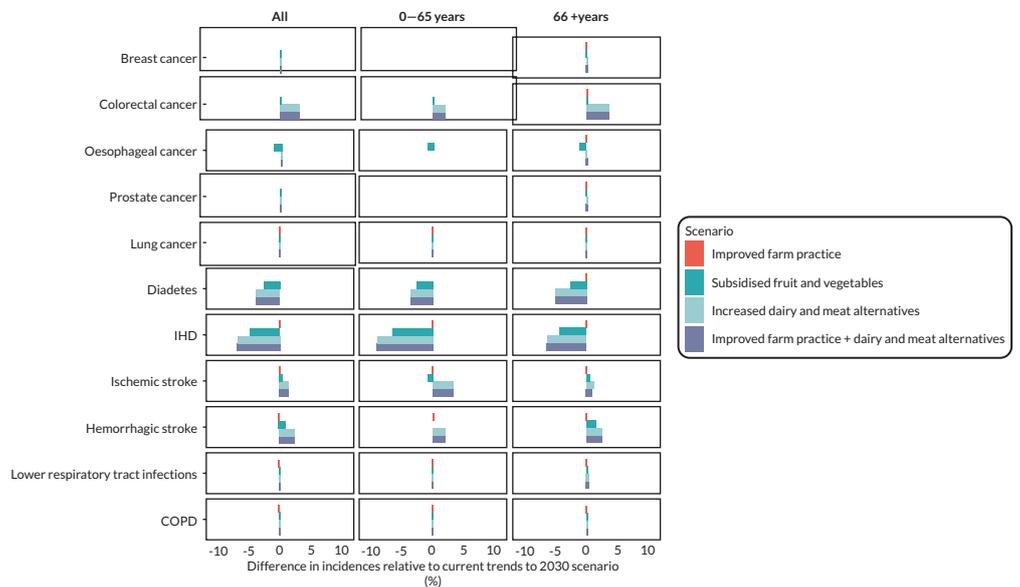
FIGURE 19 Screenshot of the prototype AMPHoRA data explorer tool.
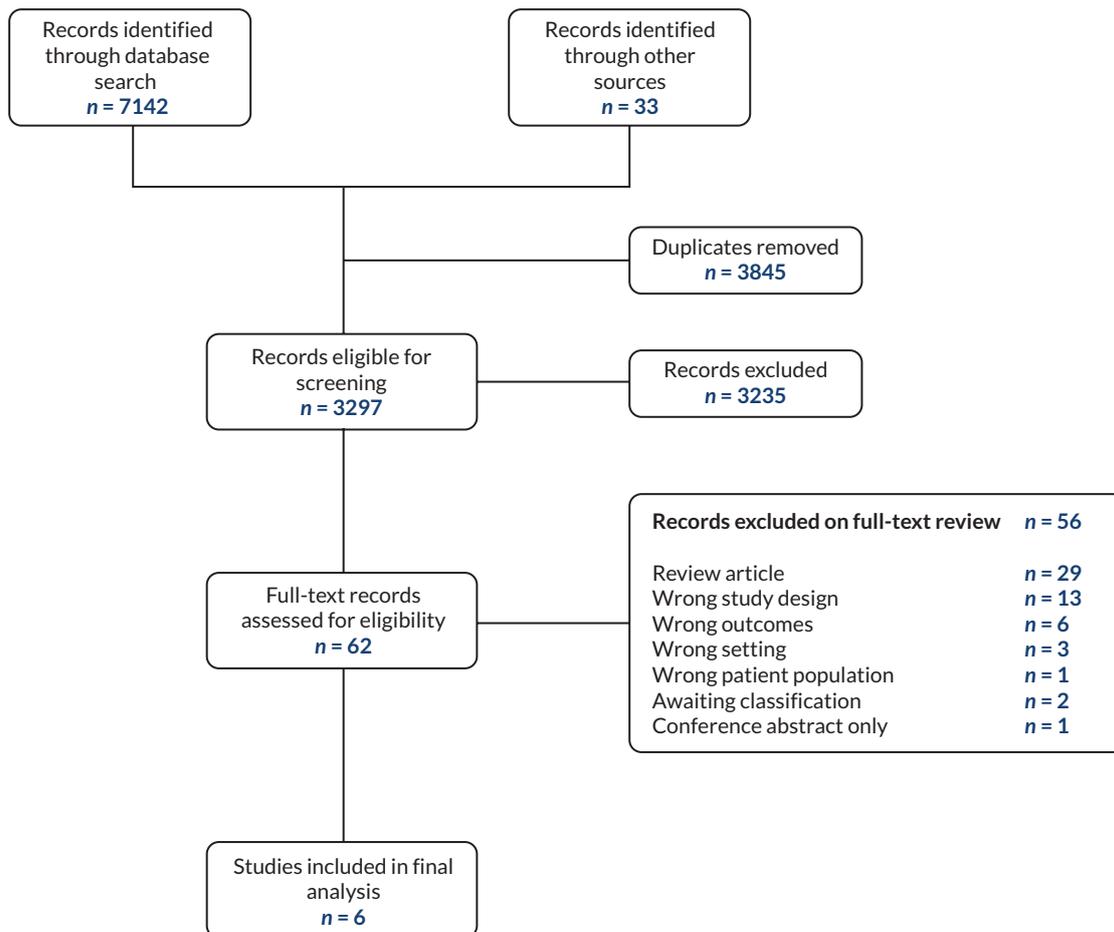
FIGURE 20 Flow chart of record screening and study identification for the systematic scooping review of the literature on agricultural APs and health.

TABLE 6 Summary of the six studies meeting the criteria for the systematic search for publications investigating the health effects of agricultural air pollution and classified clinical outcomes

Author (publication year)	Study design	Country of study	Population	Exposure	Exposure measurement method and duration	Study period	Outcome measure(s)	Result	Comments
Eduard *et al.* (2009)[69]	Longitudinal prospective cohort	Norway	4735 farmers	Various; including NH_3, inorganic dust	Personal NH_3 detection devices worn by farmers during agricultural activities. Annual exposure was derived from short-term measurements and participant-reported activity duration	Study period: 1991–6	Prevalence of:	Highest NH3 exposure compared to lowest:	Results adjusted for age, sex and smoking status (pack-years). - Compared to crop farmers, livestock farmers were more likely to have chronic bronchitis or COPD. Positive association with NH_3 exposure and likelihood of chronic bronchitis and COPD diagnosis - Inorganic dust linked to chronic bronchitis but not COPD
							Chronic bronchitis	OR_{adj} 1.8 (95% CI 1.3 to 2.5)	
							COPD	OR_{adj} 1.4 (95% CI 1.1 to 1.8)	
							FEV_1 change	45 ml reduction (95% CI 10 to 80 ml)	3.
Huang *et al.* (2019)[70]	Prospective cross-sectional	USA	All children and young adults (0–18 years) resident in the US state of Georgia	$PM_{2.5}$, with 12 source apportionment categories	Daily $PM_{2.5}$ source impacts were quantified using a two-step source apportionment approach: hybrid data fusion of Environmental Protection Agency Community Multiscale Air Quality Modelling System simulations and results from stationary monitoring stations, followed by bias correction	2005–7	Emergency department visits with:	Per interquartile range (IQR) in agricultural PM2.5 concentrations	Some associations between agricultural $PM_{2.5}$ exposure and emergency presentations to hospital for respiratory disease; however, these were null after adjustment for other sources
							Asthma exacerbation (ICD-9493)	OR 1.004 (95% CI 0.989 to 1.019)	
							Pneumonia (ICD-9480–6)	OR 1.004 (95% CI 0.986 to 1.022)	
							Acute upper respiratory tract infection (ICD-9460–5)	OR 1.003 (95% CI 0.996 to 1.009)	

TABLE 6 Summary of the six studies meeting the criteria for the systematic search for publications investigating the health effects of agricultural air pollution and classified clinical outcomes (*continued*)

Author (publication year)	Study design	Country of study	Population	Exposure	Exposure measurement method and duration	Study period	Outcome measure(s)	Result	Comments
Loftus *et al.* (2015)[71]	Longitudinal prospective cohort	USA	Children with a history of asthma (*n* = 51)	NH_3	Measurement devices placed outside of participants' homes, at various distances from livestock farms. Data collected for 24 hours once per week for 1 year	2011–2	**Outcome measure:** Shortness of breath Activity limitation Increased bronchodilator therapy usage Change in FEV_1	**Per IQR increase in weekly NH3 concentration:** OR 1.1 (95% CI 0.86 to 1.3) OR 1.1 (95% CI 0.79 to 1.4) OR 0.97 (95% CI 0.82 to 1.2) FEV_1, 3.8% reduction (95% CI 0.2 to 7.3)	NH_3 associated with a 3–4% reduction in FEV_1, but no association between NH_3, asthma severity (quantified by medication use) or asthma symptoms
Post *et al.* (2021)[72]	Prospective cross-sectional	The Netherlands	Nationwide population study (*n* = 7,735,491)	PM_{10} and proximity to livestock farms	PM_{10} concentrations were calculated by multiplying the number of animals per location with validated animal-specific and housing type-specific emission factors. Animal category-specific particle size distribution calculations used to determine nationwide distributions and exposures	2015–6	**Increased medication dispensing (surrogate marker of obstructive airway diseases)**	Increased concentrations of PM_{10} from all livestock sources (OR_{adj} 0.97, 95% CI 0.94 to 1.00) Increased concentrations of PM_{10} from cattle-farms (OR_{adj} 0.92, 95% CI 0.87 to 0.97) Increased concentrations of PM_{10} from non-agricultural sources (OR_{adj} 1.27, 95% CI 1.07 to 1.51)	Inverse association between agricultural PM_{10} and medication dispensing but positive association with non-agricultural PM_{10}

TABLE 6 Summary of the six studies meeting the criteria for the systematic search for publications investigating the health effects of agricultural air pollution and classified clinical outcomes (*continued*)

Author (publication year)	Study design	Country of study	Population	Exposure	Exposure measurement method and duration	Study period	Outcome measure(s)	Result	Comments
Smit *et al.* (2014)[73]	Prospective cross-sectional	The Netherlands	Rural population excluding people living on a farm (*n* = 92,548)	PM_{10} and proximity to livestock farms	PM_{10} concentrations were calculated by multiplying the number of animals per location with validated animal-specific and housing type-specific emission factors	2009	**Visit to primary care during study period (ICPC coding) for:** Asthma (R96) COPD (R91, R95) Allergic rhinitis (R97)	**Per IQR increase in concentrations of PM10 from farms within 500 m:** OR_{adj} 0.91 (95% CI 0.84 to 0.98) OR_{adj} 0.81 (95% CI 0.71 to 0.92) OR_{adj} 0.91 (95% CI 0.84 to 0.99)	Inverse association between agricultural PM and asthma, COPD, and allergic rhinitis diagnosis. The closer to the farm, the greater the inverse association for sheep, swine and goat farms, but positive association for mink farms. Farm exposures were not associated with higher endotoxin levels
Weichenthal *et al.* (2014)[74]	Longitudinal prospective cohort	USA	Rural population (82% farmers) in the states of Iowa and North Carolina (*n* = 83,378)	$PM_{2.5}$	6-year average satellite-derived pollution measurements augmented by results from stationary monitoring stations, and a bias correction factor	1993–2009	**Cause of death:** Non-accidental Cardiovascular disease IHD Lung cancer Cerebrovascular disease	**Per 10-µg/ m3 increase in ambient PM2.5** HR_{adj} 0.95 (95% CI 0.76 to 1.20) HR_{adj} 1.31 (95% CI 0.84 to 2.04) HR_{adj} 2.68 (95% CI 1.04 to 6.87) HR_{adj} 0.75 (95% CI 0.34 to 1.65) HR_{adj} 1.78 (95% CI 0.72 to 4.42)	$PM_{2.5}$ not associated with non-accidental deaths, and consistent inverse association if restricted to women only. Association between $PM_{2.5}$ and death due to IHD if restricted to men only. Adjustment for occupational categories did not change relationships. Separately, only diesel tractor use associated with non-accidental mortality in men only

FEV_1, forced expiratory volume in 1 second; HR_{adj}, adjusted hazard ratio; ICPC, International Classification of Primary Care; OR_{adj}, adjusted odds ratio.

(a) Deaths

(b) Incidence

(c) Life years
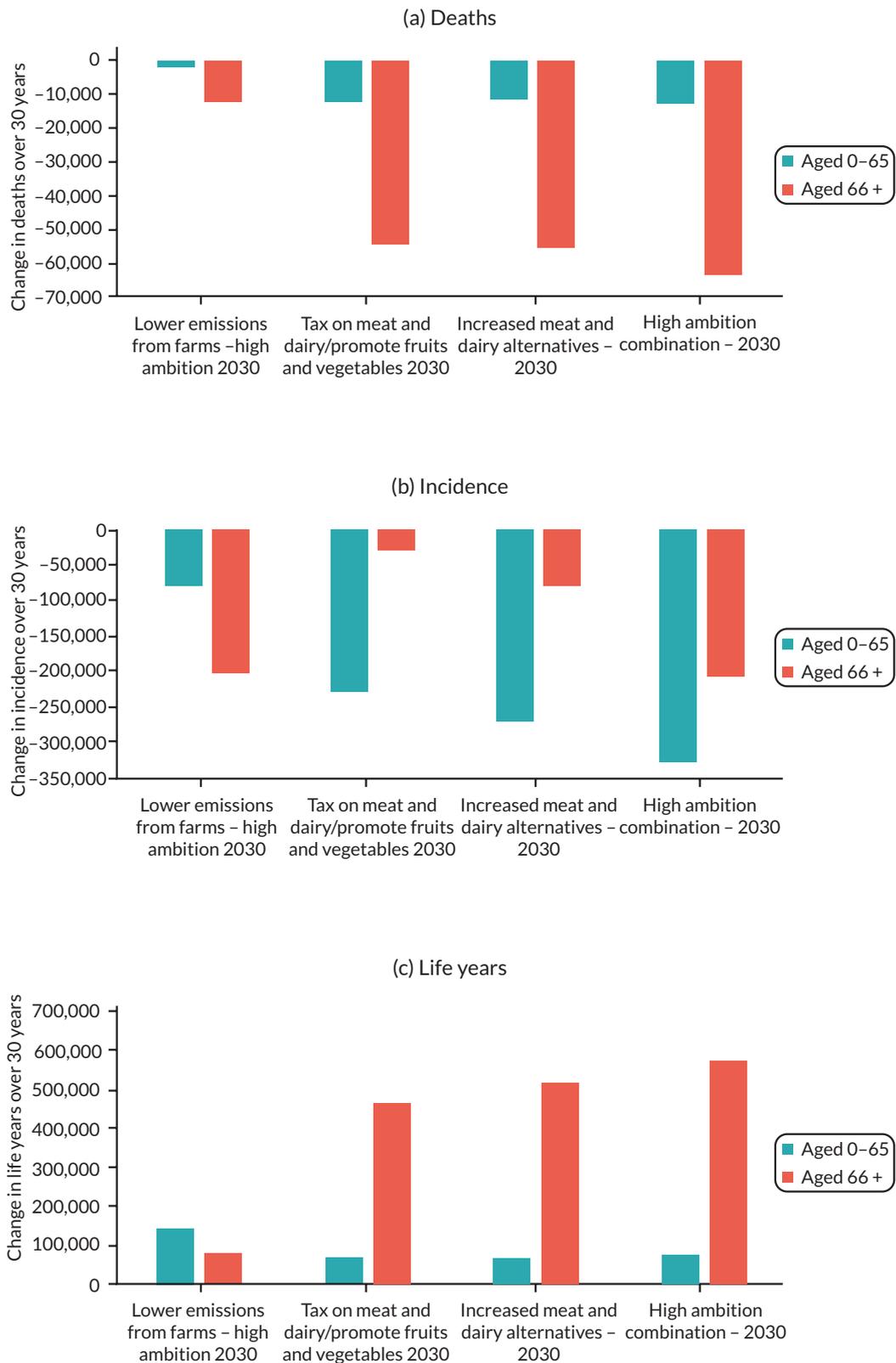
FIGURE 21 Changes in (a) deaths, (b) incidence and (c) LYs over 30 years by age group (0–65, 66 +) for each AMPHoRA intervention scenario compared to the 'Current market trend to 2030' scenario.

The benefits for mortality (and LYs) are seen predominantly at older age groups due to their greater underlying mortality rates for all investigated disease groups. For overall disease incidence, the balance of impacts with age varies across the different scenarios. The 'Lower emissions from farms' scenario (scenario 5) leads to somewhat larger benefits at older ages since the underlying mortality rates for health conditions affected by $PM_{2.5}$ air pollution are greater in those age groups. On the other hand, the dietary changes under the 'Tax on meat and dairy/promote fruits and vegetables' (scenario 10) and the 'Increased meat and dairy alternatives' (scenario 11) result in greater reductions in the number of disease cases at younger ages (below age 65) than older ages. In general, all benefits for health are most pronounced under the 'High-ambition combination' scenario (scenario 15), under which action to reduce agricultural emissions of NH_3 is combined with dietary changes that focus on switching from meat to alternative protein sources.

Relative contributions of changes in $PM_{2.5}$ exposure and diet

Figure 22 shows the contribution of changes in $PM_{2.5}$ exposure and diet to the overall health benefit in terms of deaths, incidence and LYs over 30 years by main AMPHoRA intervention scenarios. Under the 'Lower emissions from farms' scenario (scenario 5), the health impacts are entirely driven by changes in $PM_{2.5}$ exposure. For the two dietary scenarios (scenarios 10 and 11), the health impacts from dietary changes are greater than those from reductions in $PM_{2.5}$, particularly when expressed in terms of deaths averted and LYs gained where diets make up 90% or more of the impact. For disease incidence, the contribution of $PM_{2.5}$-related health impacts is more pronounced. Under the 'Tax on meat and dairy/promote fruits and vegetables' scenario (scenario 10), air pollution makes up around 40% of the reduction in disease incidence; for the 'Increased meat and dairy alternatives' scenario (scenario 11), the value is just over 25%.

Estimated health burdens by broad disease groups

A breakdown of the mortality and incidence results for each scenario by broad disease group (cancers, respiratory outcomes, heart disease, stroke and type 2 diabetes) suggests a mixed pattern of increases and decreases across the different disease groups due to the complex changes in population structure in the life table model under each scenario (see Figure 22).

Generally, all of the four intervention scenarios reduce average individual mortality rates for all disease groups. However, since all disease groups were included in a single health impact model, changes in mortality for one disease group will affect the overall population age structure and therefore will also affect deaths (and disease cases) from other causes at population level. Because the scenarios result in reduced mortality rates for all disease groups, life expectancy increases and deaths are delayed to older ages, with a larger population particularly at older ages. As a result, deaths and disease incidence increase for some diseases, especially those which have high underlying rates at older ages. In particular, the scenarios lead to large benefits in terms of reduced IHD (a disease with a large current health burden in the UK). This reduction in the health burden of IHD leads to an increased population at older ages and subsequent increases in numbers of deaths and cases of some cancers, respiratory diseases and stroke at population level (Figure 23).

Effects due to changes in population age structure

To demonstrate how changes in one outcome can affect another, consider the example of changes in IHD and stroke under the 'Tax on meat and dairy/promote fruits and vegetables' scenario (scenario 10). Figure 24 shows the increase in the English male population at the mid-income deprivation group (quintile 3) by age after a period of 30 years for each intervention scenario A–D relative to the 'Current market trend to 2030' scenario. At age 65 years, after 30 years, the population has increased by 69 (from 71,871 to 71,940), and at age 80 years, the population has increased by 103 (from 51,647 to 51,750). The result is an increase in life expectancy at birth from 81.54 years under the 'Current market trend to 2030' scenario to 81.63 years.

Figure 25 illustrates how the increased population due to the reduced burden of IHD subsequently results in more deaths due to stroke under the 'Tax on meat and dairy/promote fruits and vegetables' scenario (scenario 10), particularly at older ages. (The jagged appearance in some of the plots occurs predominantly because of the age-specific exposure-response functions.) IHD mortality rates are generally decreased at all ages under the examined scenario, and this results in large decreases in IHD deaths (Figure 25a). In contrast, for stroke, the reductions in mortality rates are much smaller than that in IHD, which results in an *increase* in deaths at the population level, largely at older ages, because the greater population more than counteracts the effect of reduced mortality rates (Figure 25b).
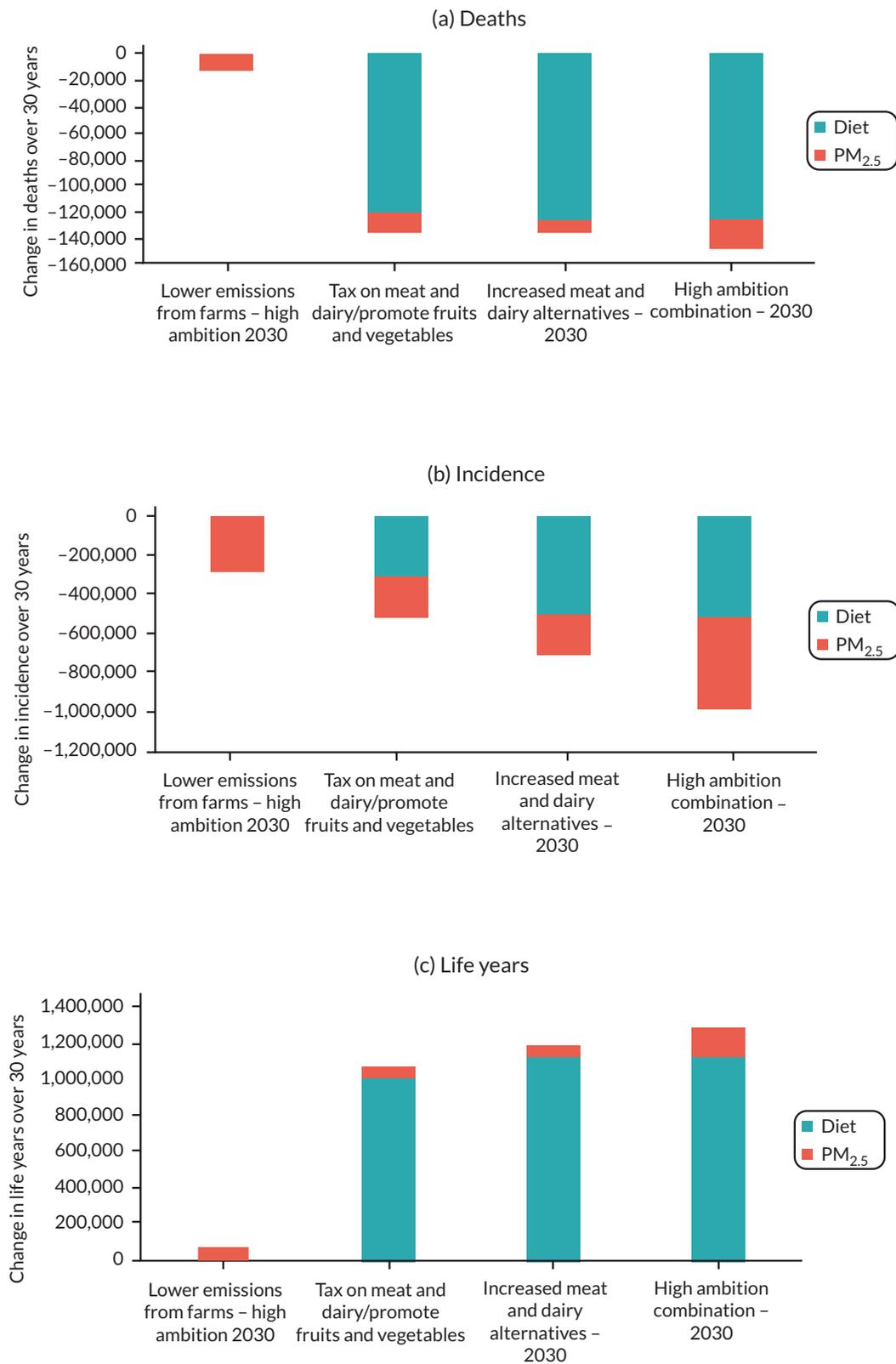
FIGURE 22 Contribution of changes in $PM_{2.5}$ exposure and diet to the health benefit in terms of (a) deaths, (b) incidence and (c) LYs over 30 years by main AMPHoRA intervention scenarios.
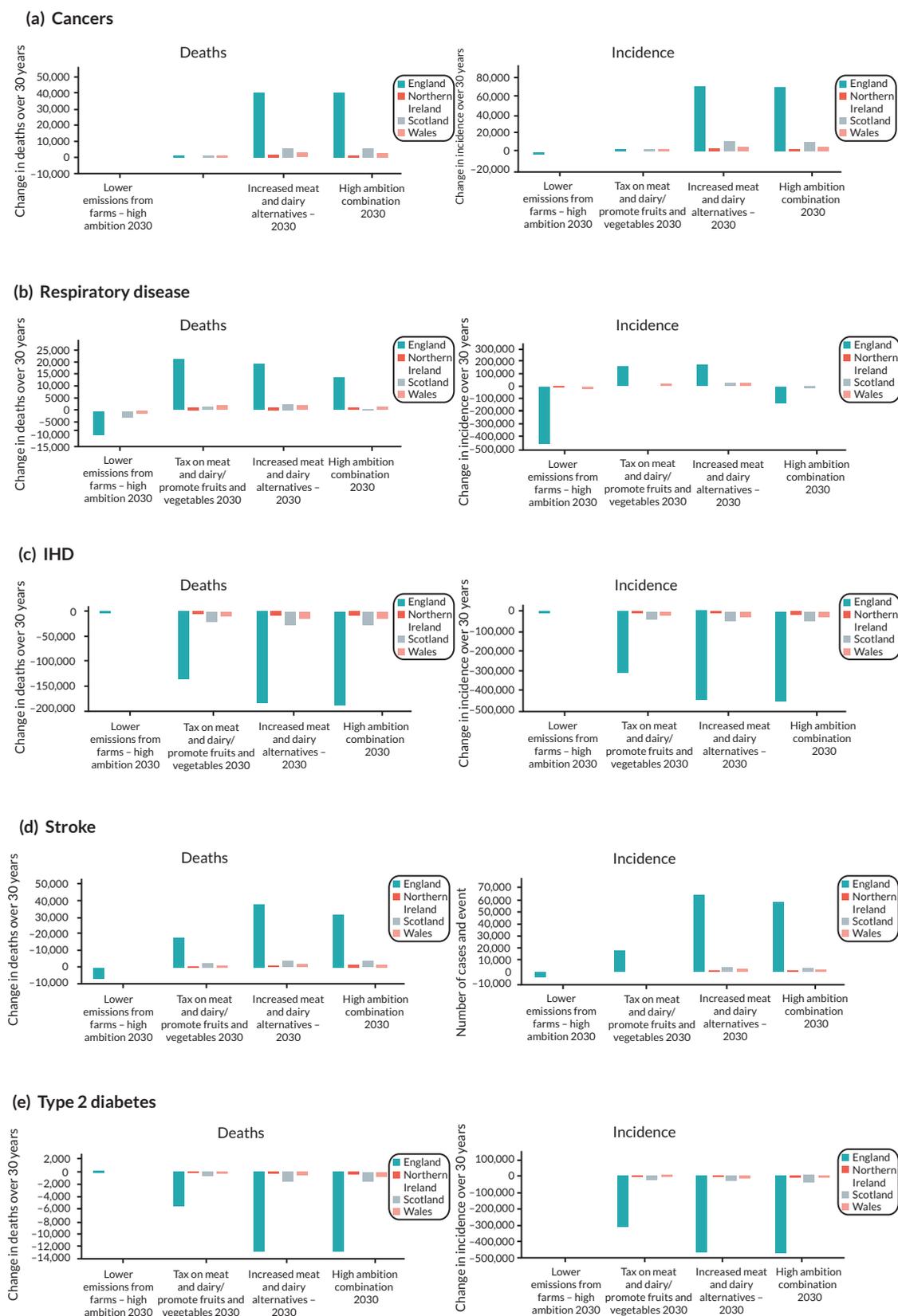
FIGURE 23 Changes in deaths (left) and disease incidence (right) over 30 years for (a) cancers, (b) respiratory diseases, (c) IHD, (d) stroke and (e) type 2 diabetes by nation (England, Northern Ireland, Scotland and Wales).
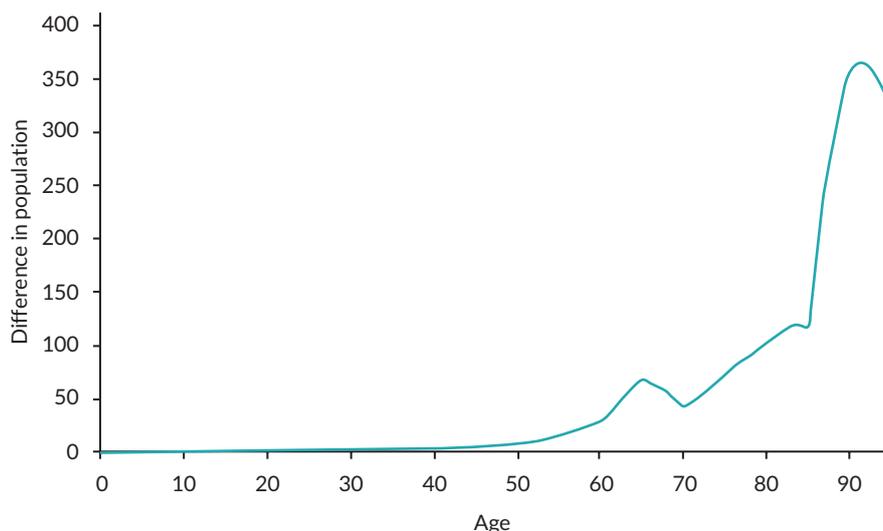
FIGURE 24 Difference in male population size by age after 30 years under the 'Tax on meat and dairy/promote fruits and vegetables' scenario (scenario 10) compared to the 'Current market trend to 2030' scenario.
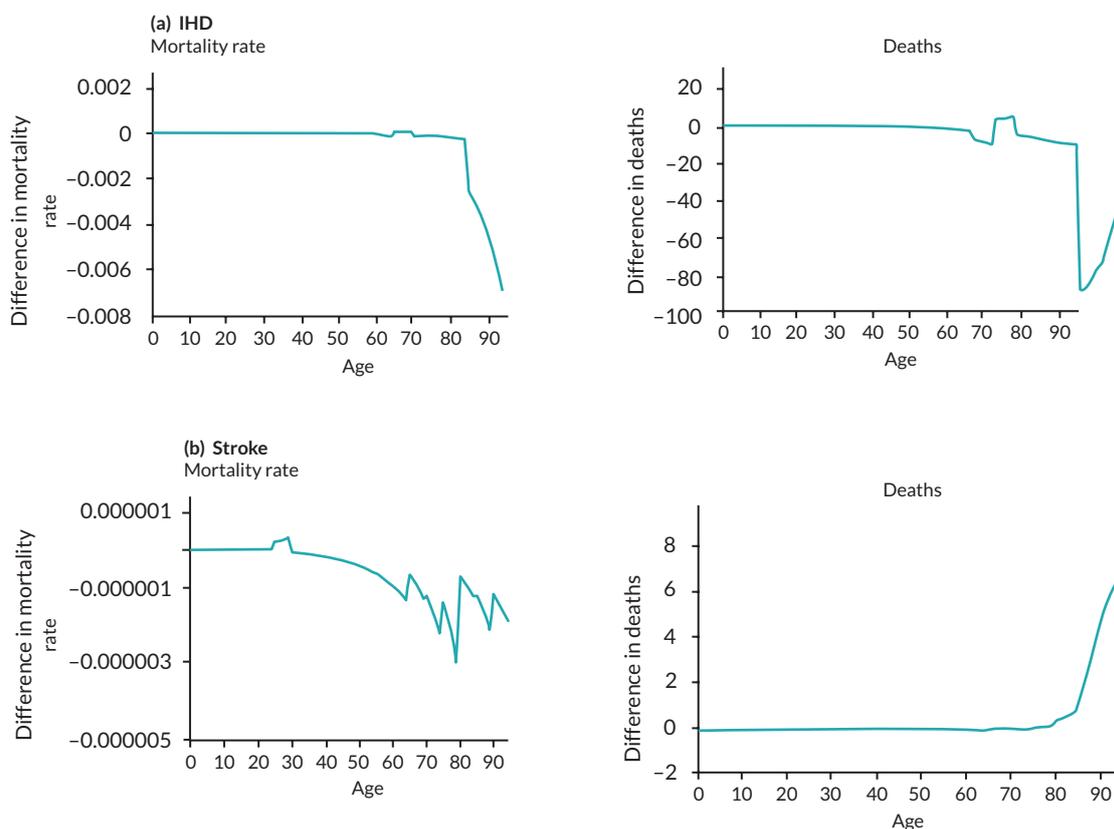
FIGURE 25 Difference in male mortality rates (left) and deaths (right) by age for (a) IHD and (b) stroke after 30 years under the 'Tax on meat and dairy/promote fruits and vegetables' scenario (scenario 10) compared to the 'Current market trend to 2030' scenario.

Impact on health inequalities

As well as effects on health at the population level, these AMPHoRA intervention scenarios also have implications for health inequalities in the UK (*Figure 26*). In the plots, income deprivation quintile 1 is the lowest average income, and quintile 5 is the quintile with the highest income. For most scenarios, though not in all cases, the health impacts are greatest for those in the lowest income quintiles and decrease at higher incomes. However, for some disease groups (IHD and respiratory outcomes), there are decreases in deaths and incidence, while for the remaining outcomes, there are increases in deaths and incidence. In both cases, the gradient is beneficial for those on lower incomes, with either greater health benefits or reduced health burdens in lower-income groups.

40
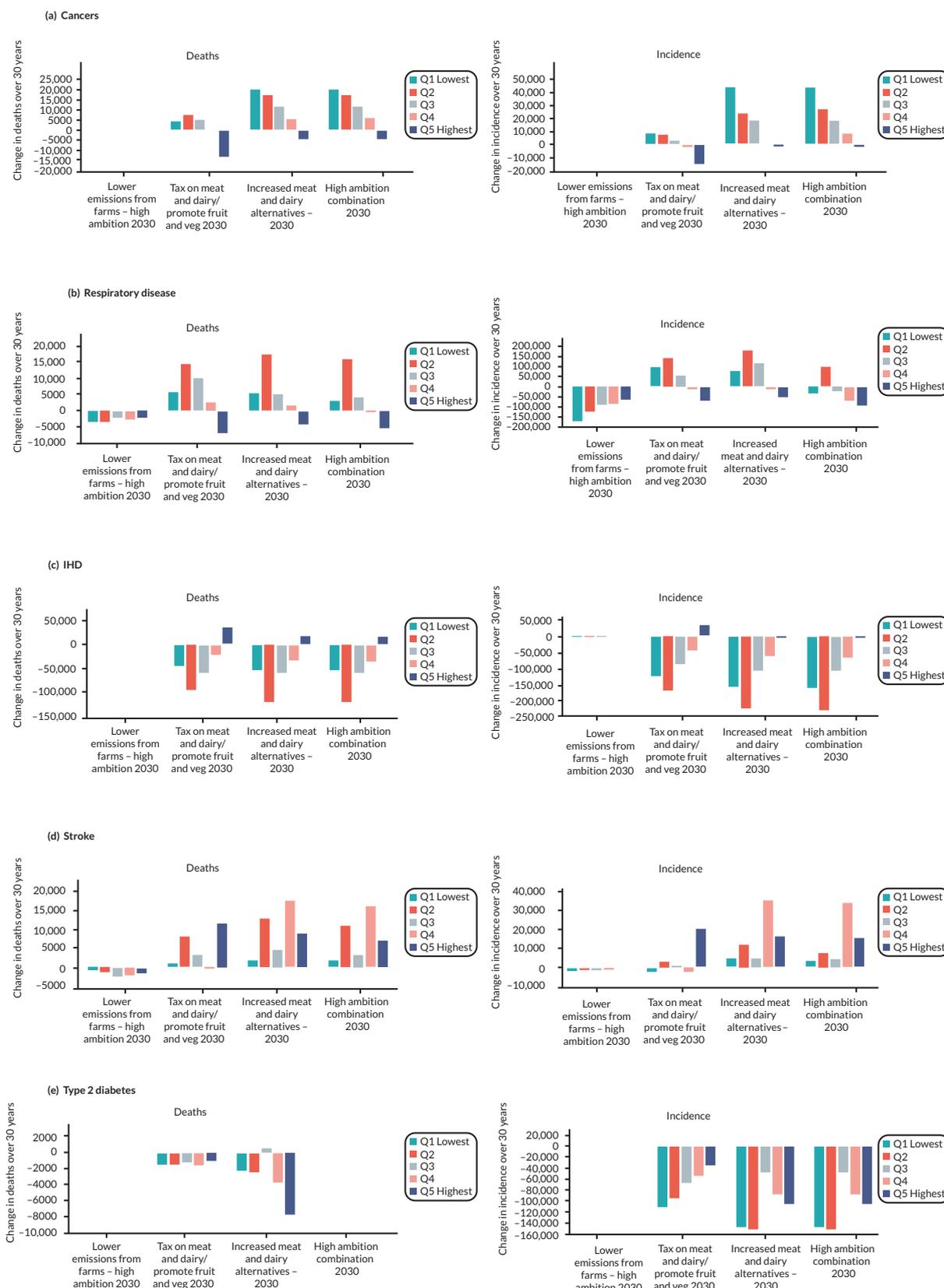
FIGURE 26 Changes in deaths (left) and disease incidence (right) over 30 years for (a) cancers, (b) respiratory diseases, (c) IHD, (d) stroke and (e) type 2 diabetes by income deprivation quintile (where 1 is the lowest income group).

Economics: is it worth reducing ammonia pollution from agriculture?

Cost-effectiveness analysis

Cost-effectiveness analysis has been carried out for scenarios 4 and 5, involving medium- and high-ambition reductions in farm NH_3 emissions, respectively, based on the use of technical measures. CEA is not possible for the scenarios involving dietary change as information on the costs of tax/subsidy schemes is unavailable and would be highly dependent on the precise way that such schemes are designed.

Data on annual NH_3 emissions and on-farm control costs for the UK are shown in *Table 7*. Costs associated with dietary change scenarios, either through tax on meat and dairy/subsidy on fruits and vegetables or through increased availability of meat and dairy alternatives have not been quantified. Subsequent analysis in this section is focused on scenarios 3 (the baseline against which others are compared), 4, 5, 10, 11 and 15 (all highlighted bold in *Table 7*). Data for England, Northern Ireland, Scotland and Wales are shown in *Appendix 3* (*Tables 25* and *26*).

Further details on the costs of the individual farm measures for scenarios 4 and 5 are provided in *Tables 8* and *9*. It is assumed here that the measures of food waste reduction and dairy low-protein diet are cost-neutral.

Cost curves for scenarios 4 and 5 addressing medium and high ambition for reducing NH_3 emissions on farms using technical measures are shown in *Figures 27* and *28*, respectively, for the UK as a whole. Scenario 5 offers roughly double the NH_3 reduction as scenario 4, largely because measures are pursued more aggressively but partly also because of the adoption of some additional measures (reduce food waste and pig in-house slurry acidification). Reducing fertiliser nitrogen has a substantial benefit per unit reduced NH_3 emission as it optimises application of fertilisers and avoids waste through excess application.

Similar charts are provided in *Appendix 3* (*Figures 37–44*) for England, Northern Ireland, Scotland and Wales, respectively. The form of the marginal abatement cost curves (MACCs) for each part of the UK are broadly similar, all showing cost savings from reduced use of *N* fertiliser and all showing a similar set of the least cost-effective measures

TABLE 7 Annual NH_3 emissions and on-farm abatement costs by scenario, for the UK

	Scenario	NH_3 emission, kt	Costs, £M/year
1	Present day (2019)	238.7	75.0
2	2019 with current agricultural emission measures removed	271.5	0.0
3	**Current market trend to 2030**	**245.6**	**80.6**
4	**Lower emissions from farms – medium ambition 2030**	**212.3**	**206.3**
5	**Lower emissions from farms – high ambition 2030**	**182.1**	**268.6**
6	Human diet trend to 2030 – no export limits	258.8	84.3
7	Human diet trend to 2030 – with export limits	253.5	84.0
8	Human diet trend to 2050 – no export limits	251.6	87.1
9	Human diet trend to 2050 – with export limits	244.2	86.6
10	**Tax on meat and dairy/promote fruits and vegetables – 2030**	**217.4**	**65.1**
11	**Increased meat and dairy alternatives – 2030**	**210.4**	**67.0**
12	Tax on meat and dairy/promote fruits and vegetables – 2050	222.3	71.3
13	Increased meat and dairy alternatives – 2050	206.6	65.1
14	Medium-ambition combination – 2030	193.0	178.0
15	**High-ambition combination – 2030**	**161.1**	**217.2**

Scenarios in bold are the principal scenarios carried into the CBA.

TABLE 8 Costs of measures for scenario 4, 'Lower emissions from farms – medium ambition 2030', £M/year per measure

	UK	England	Northern Ireland	Scotland	Wales
Urease inhibitor	12.0	9.9	0.9	0.9	0.3
Rapid manure incorporation	2.0	1.5	–	0.3	0.2
Low emission slurry spreading	20.4	9.8	6.0	2.6	2.2
Slurry store covers	37.9	25.7	1.1	5.5	5.6
Farm Yard Manure sheeting	0.1	–	–	–	0.2
Washing dairy collecting yards	5.8	4.3	0.2	0.7	0.6
Air scrubbers for pig and poultry	29.6	22.2	2.3	2.2	2.9
Dairy housing floor design	14.6	8.9	3.0	0.9	1.9
Dairy low-protein diet	–	–	–	–	–
Reduction in *N* fertiliser use	(58.9)	(42.6)	(4.6)	(7.6)	(4.0)
Total	**63.5**	**39.7**	**8.9**	**5.3**	**9.9**

TABLE 9 Costs of measures for scenario 5, 'Lower emissions from farms – high ambition 2030', £M/year per measure

	UK	England	Northern Ireland	Scotland	Wales
Food waste reduction	–	–	–	–	–
Urease inhibitor	11.3	9.5	0.7	0.8	0.3
Rapid manure incorporation	2.1	1.6	–	0.3	0.2
Low emission slurry spreading	74.7	45.1	12.6	9.6	6.6
Slurry store covers	39.1	26.6	1.1	5.6	5.8
Farm Yard Manure sheeting	1.0	0.8	–	0.1	0.2
Washing dairy collecting yards	10.9	7.6	1.3	1.0	1.1
Air scrubbers for pig and poultry	45.8	39.1	2.8	3.1	3.5
Pig in-house slurry acidification	13.3	9.6	3.2	0.6	0.0
Dairy in-house slurry acidification	50.8	35.3	8.1	2.8	5.0
Dairy low-protein diet	–	–	–	–	–
Reduction in *N* fertiliser use	(176.6)	(127.8)	(13.8)	(22.8)	(12.1)
Total	**72.6**	**47.2**	**16.1**	**1.0**	**10.6**

on the right-hand side of the figure. There is, however, some change in the order of measures and also some change in the precise estimates of cost-effectiveness for each measure, though nothing is sufficient to change the overall conclusions drawn from the charts.

While estimation of costs is based on the best evidence available, it is recognised that the data presented are average figures for both cost and NH_3 reduction and that there will be variability from farm to farm. Data to characterise the level of uncertainty that exists are not available and would require results from farm trials carried out in different parts of the country on different types of farms. An indicative estimate of ± 50% is provided here for variability at the farm level, though the aggregate results shown in *Figures 27* and *28* may be considerably more robust.

Data on GHG emissions or change in GHG emissions have also been calculated for some scenarios (see *Table 10*).
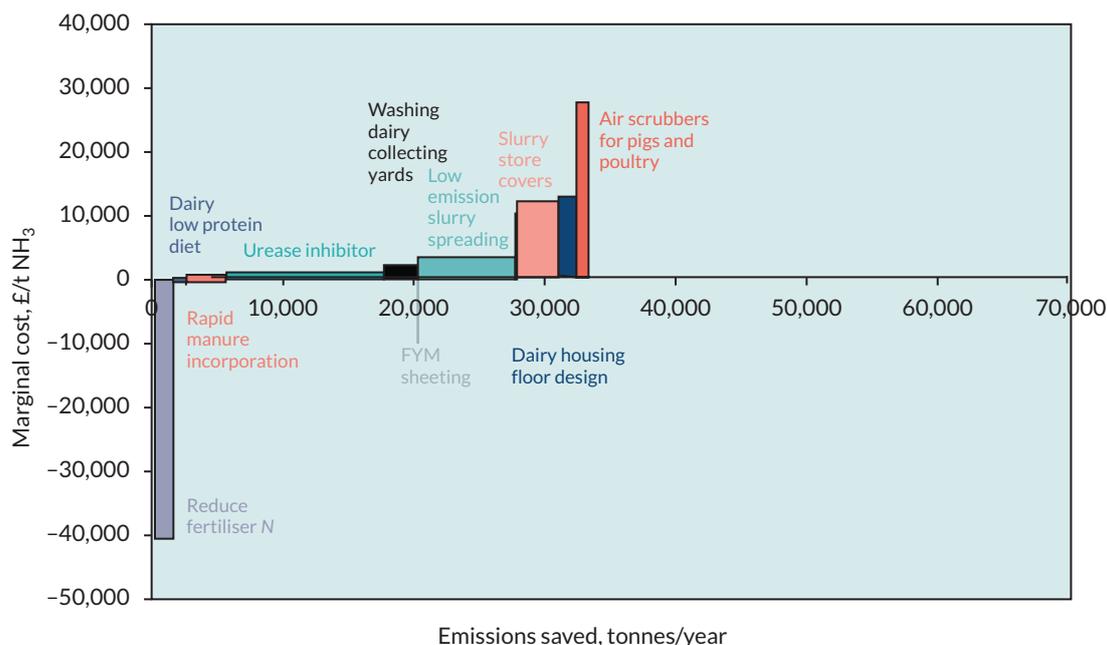
FIGURE 27 Marginal abatement cost curve for NH$_3$ abatement for scenario 4: 'Lower emissions from farms – medium ambition 2030' for the UK. FYM, Farm Yard Manure.
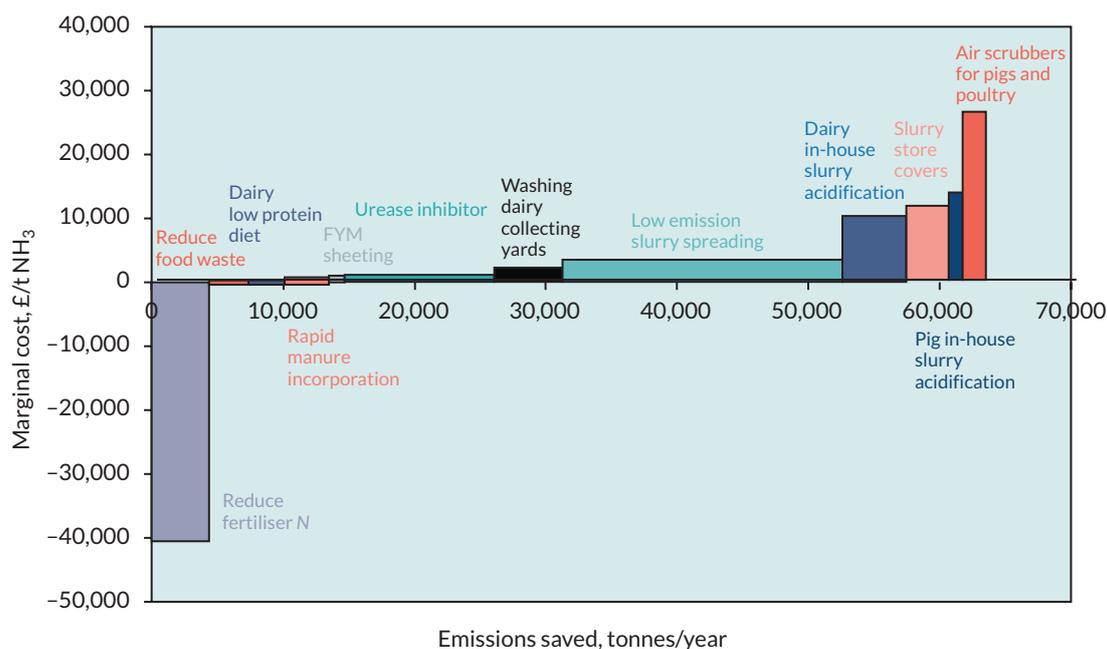
FIGURE 28 Marginal abatement cost curve for NH$_3$ abatement for scenario 5: 'Lower emissions from farms – high ambition 2030' for the UK. FYM, Farm Yard Manure.

Benefits

Results above demonstrated a complex picture for health impacts, with some effects decreasing as emission levels fall, and others, over time increasing, recognising that we all die of something at some time. Results varied across scenarios. In all cases, mortality impacts were reduced, while for some, (e.g.) cancers and respiratory diseases increased. The dynamic approach to the modelling provides a more realistic impression of how scenarios are likely to affect health in the long term than the traditional static approach to air pollution impact assessment where each condition is treated in isolation of others. As shown above, economic values have been quantified for each effect individually, making it possible, in theory, for the improvements in some effects to be outweighed by the worsening of others.

TABLE 10 Greenhouse gas emissions as tonnes CO_{2e} per year for the UK

	Scenario	CO_{2e} emission, kt	Change in CO_{2e} emission, kt vs. scenario 3 BAU
1	Present day (2019)	131,089	
3	Current market trend to 2030	119,975	
4	Lower emissions from farms – medium ambition 2030		316
5	Lower emissions from farms – high ambition 2030		1435
10	Tax on meat and dairy/promote fruits and vegetables – 2030	110,124	9851
11	Increased meat and dairy alternatives – 2030	105,073	14,902
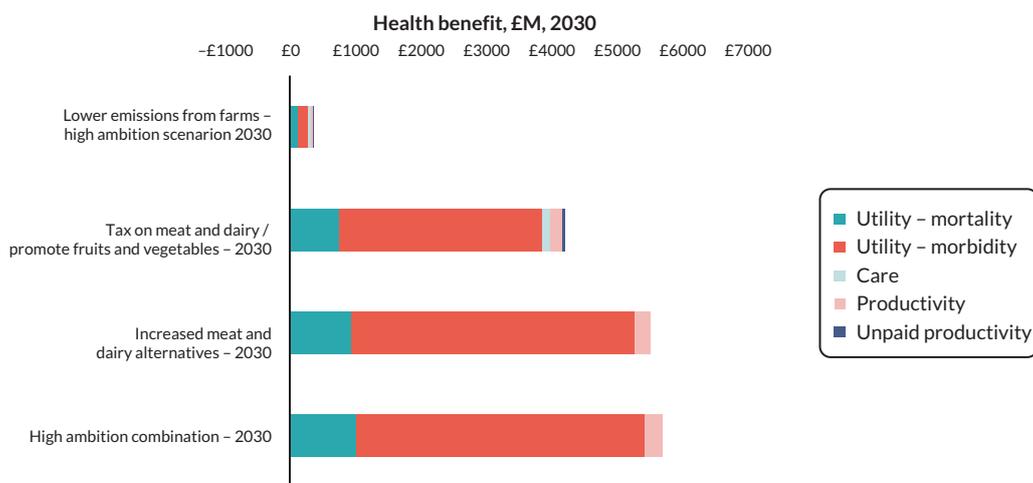
FIGURE 29 Health benefits by category in 2030.

Results by category of health impact are shown in *Figure 29* for 2030. Highest benefits are linked to the 'High-ambition combination' scenario, followed by increasing meat and dairy alternatives, tax/subsidy scheme to promote healthier eating and the high-ambition scenario for abating emissions of NH_3 at farms. The most important impact in economic terms is the reduction in morbidity linked to better diets.

The most important impact in economic terms is the reduction in utility loss to morbidity linked to better diets.

As noted already, the picture for morbidity is complicated given that there are both benefits and disbenefits linked to the options considered when effects are considered over a full lifetime. The way that benefits/disbenefits for morbidity/utility are distributed is illustrated in *Figure 30* for scenario 15 (high-ambition combination for 2030) in 2030. Effects on most cancers are slightly negative. Effects on stroke are more strongly negative. Effects on lung cancer, LRI and COPD are slightly positive. Dominating the benefits are the positive effects on diabetes and IHD. The dominance of diabetes and IHD arises due to a combination of their high level of incidence, and the duration and level of quality-adjusted life-year (QALY) loss associated with them.

The benefits of reducing GHG emissions in 2030 under the different scenarios are of a similar order of magnitude to the health benefits quantified for on-farm NH_3 controls and the dietary measures (*Figure 31*).
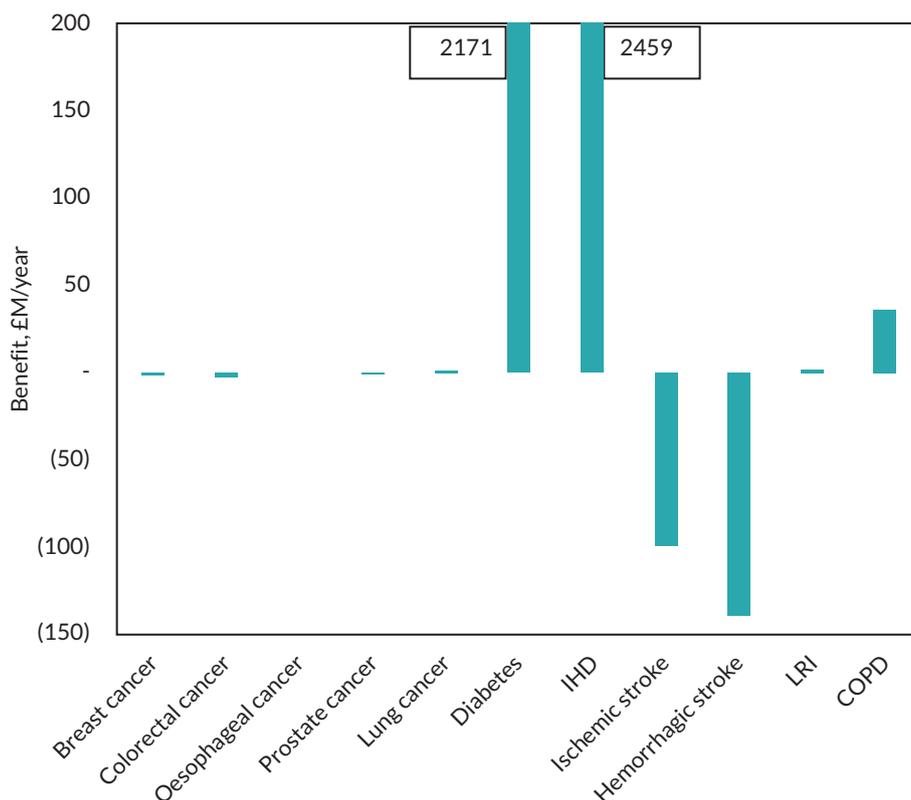
FIGURE 30 Utility benefits and costs for morbidity by health condition in scenario 15: high-ambition combination for 2030.
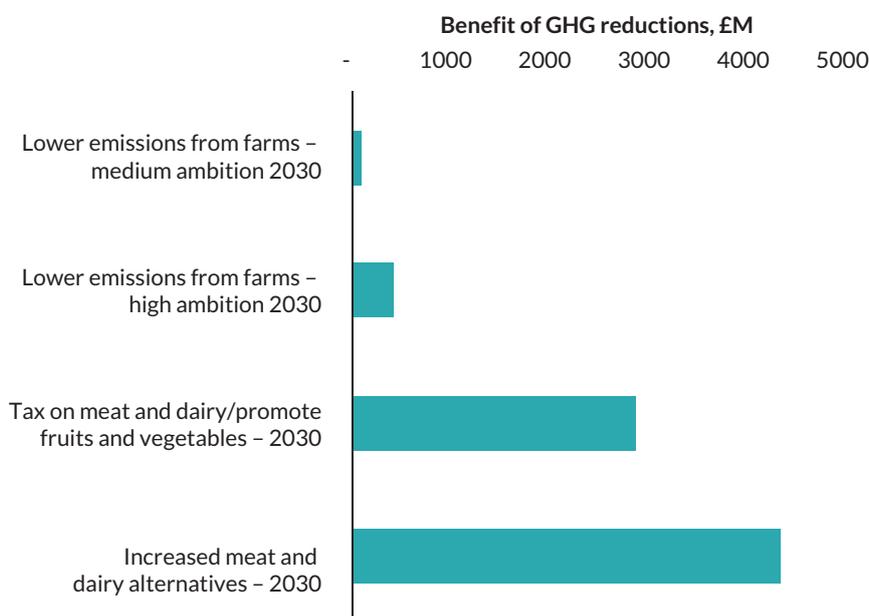
FIGURE 31 Benefits by scenario of reducing GHG emissions in 2030 for the UK.

The net present value (NPV) of the health benefits of scenarios has been calculated over periods of 20, 30, 40, 50 and 96 years (*Figure 32*). Declining discount rates have been used following the scheme described by His Majesty's Treasury (HMT) (2022). The pattern over time between the scenarios is similar to that for the single-year snapshot of 2030 provided in *Figure 29*. However, the dietary change scenarios generate far higher benefits than the technical measures on farms.
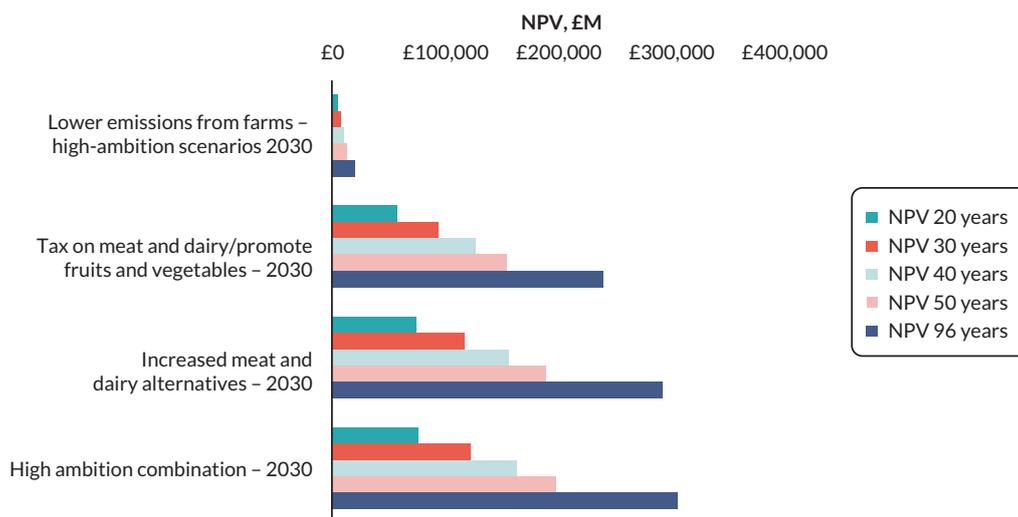
FIGURE 32 Net present value of health benefits of scenarios over different time periods.
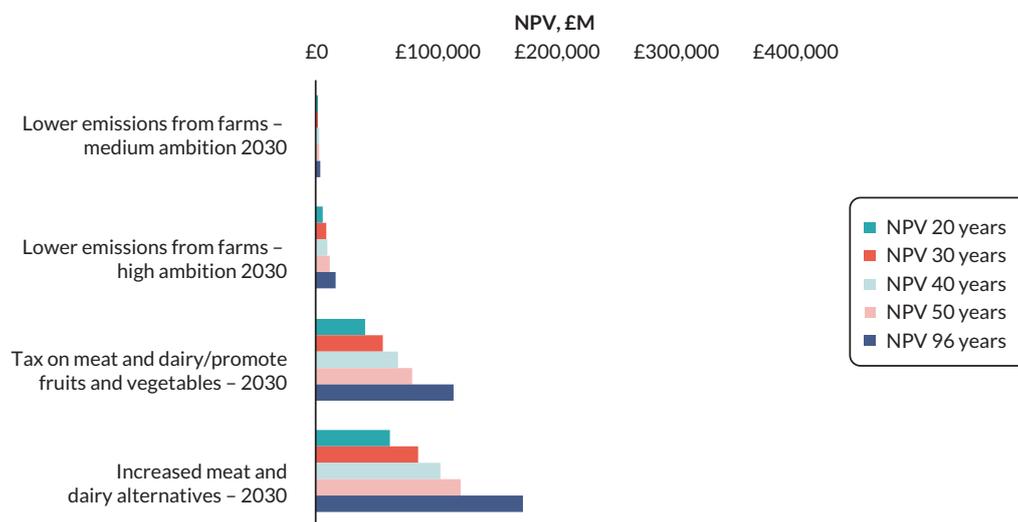
FIGURE 33 Net present value of the benefits of reducing GHG emissions over different time periods.

The benefits of reducing GHG emissions over different time periods are shown in *Figure 33*. Use of a higher discount rate for GHG savings starting at 3.5% and declining after 30 and 75 years leads to a marked reduction in NPV particularly for the longer time periods compared to the results for health benefits shown in *Figure 32*. However, results still represent potential for major benefits to society.

Cost–benefit analysis

The CBA described here focuses on scenarios 4 and 5, medium and high ambition for reducing NH_3 from farms in 2030.

As a first step, costs and benefits are compared at the scale of whole scenarios for periods of between 20 and 96 years (the latter representing the full timescale for the health impact assessment, while shorter terms are of more interest from a policy perspective). Analysis is most appropriate at the level of the UK as a whole rather than for the DAs given the transboundary nature of air pollution.

In all cases, benefits exceed costs. Benefit cost ratios increase over time, from 1.59 to 3.60 as a result of differences in the discounting of health impacts and the costs of abatement.

The comparisons made in *Table 11* do not account for variability in the costs or benefits attributable to each individual measure. This can be done by estimating damage per tonne emission (*Table 12*), focused on 2030 (by which time health impacts have started to equilibrate against each other). Estimates of benefits per tonne emission reduction are provided for:

- NH_3 health impacts using results from this study
- NH_3 non-health impacts using a figure of £487/tonne NH_3 taken from Ricardo (2023)
- estimates of cobenefits of reduced GHG emissions resulting from NH_3 abatement using data presented in *Appendix 3* (*Tables 27* and *28*) on emissions in the two scenarios and costs.

It is notable that the GHG emissions contribute significantly to the totals, particularly for the high-ambition scenario. Most of the difference is related to inclusion of food waste reduction in the high-ambition scenario. For comparison, DEFRA[76] provide an averaged UK estimate of £9667/tonne NH_3, a little lower than the NH_3-only estimate here of £10,900/tonne NH_3.

TABLE 11 Net present value of benefits and costs of scenario 5: 'Lower emissions from farms – high ambition 2030' for the UK, £M

	Benefits (£)	Costs (£)	Benefit cost ratio
NPV 20 years	4396	2765	1.59
NPV 30 years	7488	3579	2.09
NPV 40 years	10,326	4170	2.48
NPV 50 years	12,769	4610	2.77
NPV 96 years	20,067	5575	3.60

TABLE 12 Benefits, £/tonne emission reduction for NH_3 reduction

£/tonne NH_3	Scenario 4: mid ambition	Scenario 5: high ambition
NH_3 health	10,413	10,413
NH_3 non-health	487	487
Total (NH3 effects only)	**10,900**	**10,900**
GHGs non-health	2790	6647
Total	**13,689**	**17,546**

These results are combined with the MACCs above (see *Figures 27* and *28*) in *Figures 34* and *35*. For simplicity, an average benefit from reducing GHG emissions is used, although this varies between measures (this is accounted for in the following description of results).

There is a substantial surplus of benefits over costs for both scenarios, for most measures except the four most expensive (slurry store covers, dairy housing floor design, pig in-house slurry acidification and air scrubbers for pigs and poultry) compared against this study's estimate of the benefits of controlling NH_3 and also DEFRA's. Of the four measures, the first three are on the borderline of generating a net benefit in terms of pollution control, while air scrubbers for pigs and poultry has a cost more than twice that of estimated NH_3 benefits. Inclusion of benefits linked to GHG control for these measures does not make them more competitive as they create almost no (or in the case of slurry store covers, negative) GHG-related benefits.
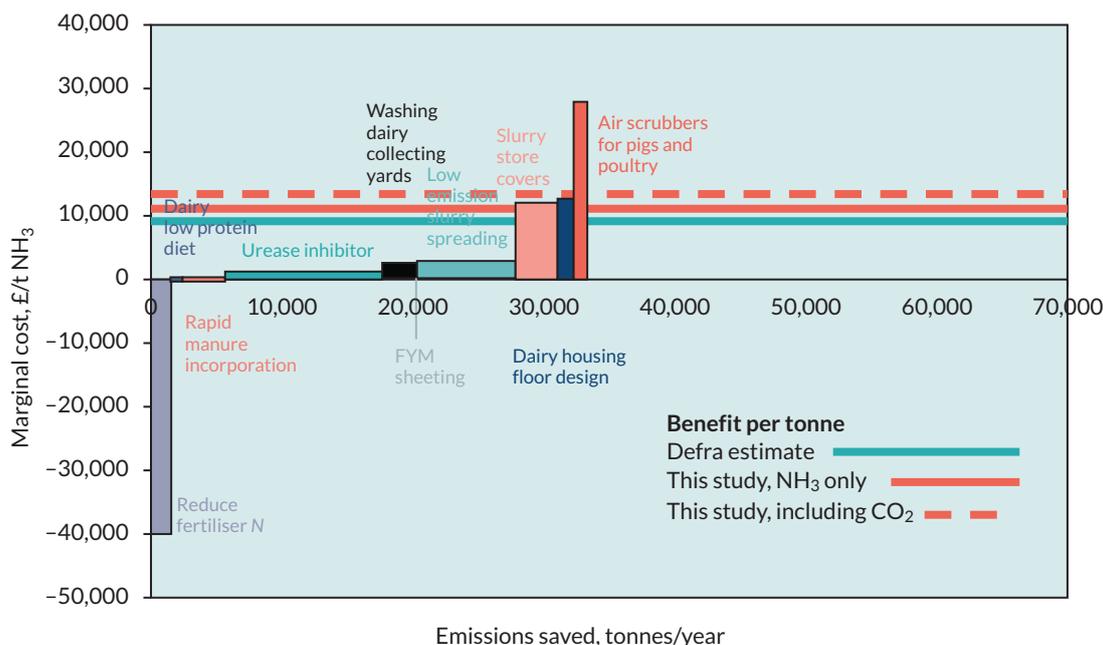
FIGURE 34 Marginal abatement cost curve for NH$_3$ abatement for scenario 4: 'Lower emissions from farms – medium ambition 2030' for the UK, with marginal benefits per tonne linked to NH$_3$ reductions added. FYM, Farm Yard Manure.
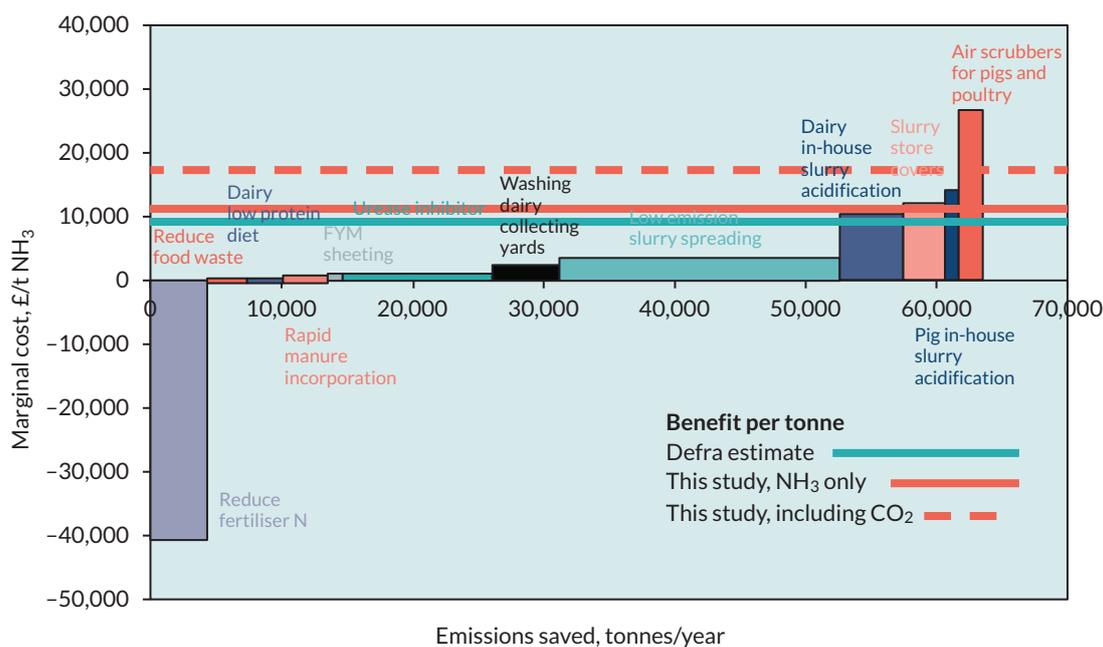

FIGURE 35 Marginal abatement cost curve for NH$_3$ abatement for scenario 5: 'Lower emissions from farms – high ambition 2030' for the UK, with marginal benefits per tonne linked to NH$_3$ reductions added. FYM, Farm Yard Manure.

Uncertainties

The main uncertainties linked to the economic analysis concern the costs of mitigation measures and variability in quantification and valuation of health impacts. Uncertainties are of limited concern for assessing the costs of most of the technical measures on farm for the purposes of AMPHoRA given the calculation of a large excess of benefit over costs extending well to the right-hand side of the MACCs (see *Figures 34* and *35*). Of more concern is variability in the cost-effectiveness of measures in different regions of the UK and between different farms. Further research to understand the extent of this variability would be extremely beneficial.

It was notable that the estimates of impacts linked to NH_3 emissions for scenarios 4 and 5 were similar based on the assumptions used in this study and those underpinning the DEFRA damage costs (Ricardo, 2023). However, the two sets of results support one another to only a limited degree given the differences in the dispersion modelling, response functions and valuations used. The strong differences that are present in the range of benefits included in the analysis highlights potential for significant differences in results. This is reinforced by the dynamic approach taken here to modelling health impacts compared to the static approach of DEFRA (and almost all other analysts in this area), where impacts are quantified in isolation of one another.

Chapter 4 Discussion/interpretation

Key findings on air pollution from agricultural activities and dietary change

- Relatively modest emission reductions are achieved in the scenarios through implementation of technical measures – difficulties/feasibility/costs of mitigating the large number of often-diffuse emission sources across the agricultural sector.
- Much greater impacts were achieved through the combination of technical and dietary measures, largely due to the differences in air pollution produced by different food groups.
- There are numerous uncertainties regarding the direct link between UK food consumption and UK production of agricultural commodities. These will be influenced greatly by market drivers (international as well as national) and the policy/legislative framework.
- UK food security must be balanced between feasible levels of home production and the importance of not 'offshoring' emissions associated with imported food.

Key findings on health impacts of agricultural air pollution and dietary change

Systematic scoping review of the health literature

We performed a systematic literature search of academic publications investigating associations between agricultural-derived air pollution (notably NH_3 or secondary PM derived from NH_3) and clinically defined health outcomes (see *Appendix 1*). The search identified a scarcity of robust epidemiological studies on the health effects of the agricultural APs, NH_3 or NH_3-derived PM. The limited studies available (six studies; *Table 6*) showed heterogeneity in methodology and inconsistent associations between pollution exposure and health outcomes. No consistent associations were found for morbidity or mortality. Indeed, four studies included in our analysis found either no association or an inverse association between pollution exposure and health outcomes. However, an ongoing examination of the more recent literature has identified new studies finding associations between agricultural PM and health outcomes, albeit still very heterogeneous in nature with few studies looking at the same pollutant-outcome pair. An updated literature search is underway to systematically review the new data, which will be developed into a research manuscript for publication in the environmental academic journal.

Our initial scoping review allows us to make a number of considerations. Firstly, studies directly measuring NH_3 on farms must consider the large number of other exposures common in this occupational setting that may also influence health outcomes, such as exposure to biological dusts, micro-organisms, diesel exhaust from farm machinery, gases from grain stores and chemicals, such as pesticides. Secondly, the scope of our review was restricted to ICD code-classified health outcomes, and further systematic searches should address subclinical outcomes, such as lung function, blood pressure and blood biomarkers. Thirdly, life-course exposure, especially during childhood, merits a purpose-defined review, to clarify the influence of AP exposures on allergic conditions later in life. Lastly, toxicological studies in cells and animal models suggest that pure ammonium nitrate and sulfate have relatively little direct toxicity, thus further research is needed to address changes in the properties of SIAs in different atmospheric conditions, and with different copollutants, to establish how such changes to the PM may subsequently impact health.

The classification and specificity of exposure of agricultural pollutants, notably secondary PM derived from agricultural sources, represents a major obstacle in assessing burden to health. Given the high proportion of PM linked to agricultural emissions, further research is urgently needed to evaluate the impacts with objective health outcome-based population studies that use standardised reporting and measuring tools, in particular large-scale population studies with source apportionment that cover both urban and rural populations.

Modelling health impacts

The health modelling analyses compared number of deaths, number of incident case and events, and LYs gained over 30 years, of selected 2030 scenarios ('Lower emissions from farms – high ambition', 'Tax on meat and dairy/promote fruits and vegetables', 'Increased meat and dairy alternatives', 'High-ambition combination') compared to the 'Current market trend to 2030' scenario. For all scenarios, deaths and incidence from all causes combined decreased and LYs gained increased, with the greatest benefits predicted in the over 66. Most of these benefits were brought about by predicted changes in dietary factors with a lower contribution from changes in $PM_{2.5}$ exposure. These differences were mainly driven by the impact of improved diets on IHD, which is the major cause of death in the UK. Reductions in $PM_{2.5}$ had the greatest impact on respiratory outcomes. For cancers, there were little benefits from the scenarios; this might have been the results of decreasing dairy, which is associated with lower PC outcomes; or it could reflect the lower impact of diet on these outcomes compared to IHD.

Scenario benefits for IHD, T2DM and respiratory outcomes were more evident for lower-income groups, with those in lower quintiles of EHIs having lower incidence or death compared to higher-income groups. The 'Tax on meat and dairy/promote fruits and vegetables – 2030' scenario, in particular, could be particularly beneficial, as it would make fruits and vegetables more affordable for a group whose low intake put them at increased risks.

Our scenarios entail relatively modest dietary changes, which would be feasible for most groups. The 'Tax on meat and dairy/promote fruits and vegetables' scenario would entail increasing fruits and vegetables by a little more than one portion per week and meat by one serving a week (such as two small/medium-grilled sausages or one-quarter-pound burger or two small lamb chops). In the 'Increased meat and dairy alternatives', the changes would be a bit more ambitious: reducing meat by two servings per week and increasing pulses by 2–3 servings per week (such as one and a quarter can of cooked beans or lentils). This is encouraging, as we show that even relatively modest changes would result in large health impacts. These reductions are in line with Intergovernmental Panel on Climate Change recommendation of reducing meat by 20% by 2030 and 35% by 2050.

Limitations of the diet modelling (taken from the published paper):[77]

- The Living Costs and Food survey is household purchasing data which likely overestimates intakes as food waste is not accounted for. Including food waste might also give a more realistic picture of the environmental impact of food systems. The data are based on self-reported estimates of food purchase and thus subject to recall bias and possible under-reporting of undesirable food items, such as confectionery and alcohol. However, receipts of purchases were used in the Family Food survey, making it more reliable than just using questionnaires.
- There is no certainty that future trends will continue in the same direction as past ones. This type of analysis cannot account for unpredictable events and ignores other potential drivers of intake, such as future trade deals, environmental shifts and policies that affect availability and price.
- The price elasticities used in the 'Tax on meat and dairy/promote fruits and vegetables' were from 2009; it is possible that consumer preferences change over time, meaning that their price responsiveness can change as well.
- We used DCE studies to predict future consumer behaviour for the 'Increased meat and dairy alternatives', but these are based on hypothetical choices in researcher-controlled settings, meaning the stated preferences may not translate into real purchases and other influences apart from price and taste might be or might become important. The studies we used were based in the USA and Canada and might not represent.
- The GHG factors applied in our study are based on current carbon production intensity and do not take into account potential future improvements in energy efficiency and use of renewables, which would result in lower CO_2 estimates of UK consumers. However, our predictions of plant-based meat and dairy substitute intakes are likely to be conservative given the sharp increase in the most recent years (Alae-Carew *et al.*, 2022).[78]

Limitations of the health modelling:

- The health model performs separate calculations for males and females for each nation of the UK (England, Northern Ireland, Scotland, Wales) and each income deprivation quintile. In addition, all disease outcomes were included in a single model (with multiple exposures), meaning that impacts on one outcome can affect the others. There are also

complex effects that arise as a result of population ageing (as highlighted in *Results*). In combination, these features make the results complicated and hinder interpretation.

- Given the complexity of the newly developed model, at this stage it has not been possible to perform uncertainty analyses.
- There are a number of simplifications and assumptions in the model. Key among these are: the assumption that the GBD RRs can be used for both mortality and morbidity, general limitations of the GBD RRs (e.g. possibility of residual confounding), the assumption that RRs are multiplicative, the use of (gender-, age- and disease-specific) population average mortality and incidence rates, the relatively crude adjustments made to the underlying mortality and incidence rates to account for income deprivation, the use of UK average dietary data to represent the four nations of the UK (i.e. we did not account for differences between the nations).

Key findings on the costs and benefits of reducing air pollution from agriculture

Key issues from the economic analysis

In the comparison of results for scenarios involving dietary interventions with those concerned with NH_3 abatement on farm, it may be concluded that action on diet is so dominant in terms of the benefits generated that it should be the sole focus of further action. However, this would be to overlook both that the agricultural measures generate benefits in excess of costs and that the dietary change measures considered here reduce but do not eliminate NH_3 emissions.

The magnitude of NH_3 emission changes identified here is important. UK emissions of other major APs have fallen considerably since their peak levels in the 1970s and 1980s, SO_2 by 98%, NO_x by 78%, PM_{10} by 79% and $PM_{2.5}$ by 85%.[75] In contrast, emissions of NH_3 have fallen by only 17%. The scenarios investigated here demonstrate that there is potential for much larger reductions in NH_3, by up to 50% of their peak level of 320 kt/year in 1984 under the high-ambition combined scenario (scenario 15). As agriculture is far and away the dominant source of UK NH_3 emissions, it is not feasible to rely on action in other sectors to reduce emissions (*Figure 36*).

The CEA demonstrates that significant emission reductions can be made at little cost. The results presented above demonstrated that benefits per unit emission calculated here, and separate estimates from DEFRA (£9667/tonne NH_3), exceed costs for measures covering 83% of the quantified potential for emission reduction for scenarios 4 and 5 (lower emissions from farms – medium/high ambition 2030 for the UK). DEFRA (2023) also provide lower and upper bound
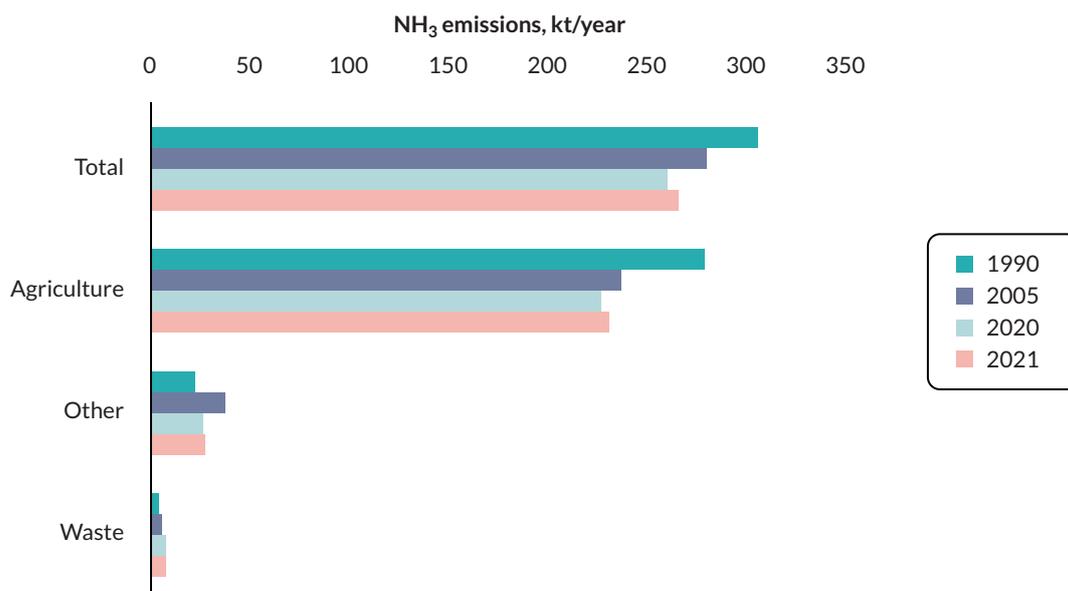
FIGURE 36 UK emissions of NH_3 by source since 1990. Data source: DEFRA.[75]

estimates for damage. The lower bound estimate (£3727/tonne NH_3) gives the same outcome by virtue of cost per unit emission rising steeply between the measures 'low emission slurry spreading' and 'dairy in-house slurry acidification'. The assumptions underpinning the DEFRA lower bound are very conservative when compared to the current literature on health impacts of air pollution, and so this outcome, alongside the results generated in this study, strongly supports the case for significant further controls on agricultural NH_3 emissions. Moving to the upper bound estimate from DEFRA (£26,172/tonne NH_3) would leave only one measure (air scrubbers for pigs and poultry) generating a net cost, covering only 3% of the potential emission cut.

The results of analysis show that health benefits of dietary change have potential to be very large. This message is extremely important, given an aversion in governments in many countries towards policies that might be considered to impinge on people's private lives and choices. At issue here is the extent to which people are well informed in the choices that they make, and also the extent to which current behaviour is influenced by external forces, such as the marketing techniques used by manufacturers, retailers, those portraying 'desirable' lifestyles and so on. The impact of what might be termed 'modern diets on health' represents a case of market failure leading to outcomes that many or even most people do their best to ignore as they grow older. The magnitude of impacts associated with such diets demonstrates that it is a space where some level of government intervention has potential for significant benefit for the population.

The dynamic approach taken to modelling health impacts in AMPHoRA provides a more realistic perspective of the way that policies affect health over a number of years than more standard approaches that consider each health impact in isolation. For this reason, the results have shown a reduction in some impacts but an increase in others at a later time. That this is the case is obvious from the most rudimentary consideration of health and ageing, so it is important that it is factored into analysis.

However, the dynamic approach to impact quantification creates a challenge for economic valuation, as it requires a high level of consistency in the valuation process across a wide range of impacts to ensure that outputs capture the correct balance overall. The approach used here has been to identify recent cost of illness studies carried out for the UK that provide estimates of healthcare costs and productivity losses and to couple those with QALY-based estimates of utility values. Inevitably, studies are needed from a range of sources, as each tends to focus on one impact or a narrow group of impacts. Some disparity was noted in estimates made for single conditions, for example, from the studies of Laudicella et al.[64] and Frontier Economics[65] for cancers. There are also differences between studies in the precise scope of valuation work, for example, whether or not costs linked to unpaid productivity are included. While the data gathered here represent a more comprehensive collection of valuation estimates than those used in earlier studies investigating air pollution impacts on public health, further work to improve the consistency of estimates will be useful.

The research has highlighted the importance of coupling actions across policy areas, here covering air pollution, dietary health and climate, giving potential for strong cobenefits. Isolating actions by individual policy headings increases the risk of inefficiency in policy. This inefficiency could make it more costly to reach targets across a basket of measures, or (where specific targets do not exist) generate lower benefit per unit of expenditure than is possible. This is a difficult problem as much policy work is organised in a way that does not encourage working beyond the boundaries of individual subject areas, and consideration of a wider set of objectives may be considered to weaken potential for delivery of targets in specific areas. Serious thought needs to be given to how policy development structures can take a wide range of factors into account in order to optimise the cobenefits that exist and gain the greatest benefit for money spent. The existence of trade-offs needs to be considered also – here evidenced by the rise in some types of health impact, such as some cancers, while others are reduced. Efficient policy-making demands that such trade-offs are identified and their importance evaluated so that they can be mitigated for to the extent possible. Where mitigation is not possible, policy-makers should at least be aware that a trade-off is present.

While the emphasis of this research is on health impacts, emissions of NH_3 contribute also to eutrophication of ecosystems, where excess deposition of nutrient nitrogen promotes the growth of common species at the expense of those that are adapted to growing in low nutrient conditions, leading to a reduction in biodiversity. Rowe et al.[79] reported exceedance of the critical load for nitrogen over 68% of nitrogen-sensitive habitats in the UK (63,470 km,[2] which is roughly one-quarter of the total UK land area). Exceedance of critical levels for gaseous NH_3 was estimated

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for 6.3% (15,455 km^2 of the total UK land area) for higher plants and 69% (169,409 km^2) for lichens and mosses. These figures represent significant threats to UK biodiversity. While some account is taken of risks to ecosystems in the economic analysis based on the results of Ricardo (2023), the approach taken may be biased to strong underestimation of public preference for ecosystem protection expressed in economic terms. One reason for this concerns the use of valuations based on individual willingness to pay (WTP) as the measure of value. Individuals are unlikely to consider ecological health as a purely private good and expect public funding alongside their own 'WTP'.[80] Further information to indicate the extent and form of damage to ecosystems, and the way that it is anticipated to evolve over time, would be an important input to decision-making.

Assessing costs of tax/subsidy schemes to influence public behaviour

It is possible that a tax on meat and dairy coupled with a subsidy for fruits and vegetables could be neutral for the average consumer, with money raised from the tax being fully used to provide the subsidy. Alternatively, the costs of running the tax/subsidy system which are not quantified here could be taken out of the tax raised before subsidies are allocated, generating a net cost to consumers. A system for taxing meat and dairy could, in theory, be set up at little cost given that retailers are accustomed to the concept of sales taxes in the form of value-added tax (VAT). There would be some cost associated with adjusting accounting procedures and familiarisation with the new regulation, but these could be small.

Thought needs to be given to defining the scope of a tax on meat and dairy and how it applies to different products as the following examples indicate:

- Should all cheese (e.g. cow, sheep, goat or hard and soft cheeses) be taxed at the same rate?
- Would a tax apply only to goods that are entirely meat or dairy (e.g. a pint of milk or a pork chop) or to all goods containing any meat or dairy produce (e.g. cakes made using milk powder, salami pizzas)? And then, would the tax apply to the whole article or only its meat and dairy content?

The importance of definition in the context of differential taxation of food products was previously illustrated by the court case where food manufacturer McVities successfully challenged UK authorities over the definition of Jaffa cakes as biscuits rather than cakes, thus avoiding VAT.[81]

There is also a question of the point at which the tax is levied. The simplest option is almost certainly to levy it at the point of production or import, which would make it easiest to capture use of meat and dairy in other products. However, by the time that goods are on sale, the effect of the tax on the price of goods may be diluted or lost altogether. The tax raised would still have the benefit of providing funding for the subsidisation of fruits and vegetables, but it could lose much of its power to drive public behaviour away from meat and dairy products.

The mechanism for payment of subsidies to consumers may also not be straightforward to set up and manage, as it is in large part dependent on the way that retailers price the goods that they sell. The effect on public behaviour may be reduced by pricing and marketing strategies on other goods, as illustrated by the debate around 'buy one get one free' ('BOGOF') deals, and strategic placing of goods in stores to promote sales. It is notable in this respect that the Soft Drinks Industry Levy in the UK (the SDIL or 'Sugar Tax') is structured in a way to affect the behaviour of producers at least as much as consumers.[82]

None of this is intended to suggest that a tax/subsidy system to promote fruits and vegetables and reduce demand for meat and milk is a bad idea. However, the design of an effective system that encourages behaviour change in the population in the way and to the extent intended is not straightforward and neither is assessment of the costs and benefits of such schemes. However, the recent example of the Sugar Tax shows that systems can be devised in a way that influences both producers and consumers.

A further issue concerns the impact of behaviour change on farmers. There would be costs involved in converting farms away from meat and dairy production, and for some farms, change would not be viable. Farmers may be able to make up for a change in UK demand by increasing exports, though this would offset mitigation of APs. Government may choose to subsidise farmers directly through land management reforms aimed at improving biodiversity, though this naturally has a cost and its own set of benefits.

Confidence in the results

Uncertainties exist at all stages of the work presented here, for example:

1. Variability in the cost-effectiveness of emission control options on farms across the country, given differences in farm size and type, soil conditions, weather conditions, etc.
2. Alternative perspectives on which health conditions should be quantified, with clear differences between those selected here and those considered in the damage cost work of DEFRA (2023).
3. Selection of response functions from the health impact literature.
4. Differences in the coverage of the various elements of cost for health impacts, covering utility losses, primary, secondary and ongoing care needs, and productivity losses in both paid and unpaid work.

Discussion of uncertainties can give the impression that little is known with confidence. It is thus important to highlight elements that are known with a high level of uncertainty. Key here is the linkage of air quality and diet to various health conditions: while there may be debate about precise response functions and valuations, these linkages can be considered robust given the body of evidence that they are based on. A substantial body of literature also supports the view that these impacts are sufficiently large as to warrant policy evaluation with a view to understanding potential policy interventions. Modelling of pollutant chemistry and dispersion certainly contains uncertainties, but results are supported by extensive measurement of air quality across Europe and various model intercomparison exercises that have been carried out in recent decades. Emission factors for NH_3 on farms, and the emission savings linked to various control measures, have also been extensively researched. So while there are uncertainties in the analysis, they are only a part of a larger picture where many elements are well known. The research team considers that the main conclusions reached here are robust.

Research priorities

From a value of information perspective, the major research priority linked to this research concerns the design of tax/subsidy systems for promoting behaviour change for healthier diets. It is important to get such a system right for several reasons, including to improve understanding of:

- How schemes would work in practice?
- How schemes can efficiently change public behaviour in the way intended?
- Impacts on the farming sector.

This is identified here as a major research priority given the magnitude of benefits identified for dietary change.

A second priority concerns identification of mechanisms through which changes at farms would be financed. The extremes range from farmers paying the full cost of measures taken at farms through to government fully subsidising such changes, for example, using funding through green bonds.[83] The measures considered here have benefits for the three main objectives of green bond finance – climate mitigation, pollution reduction and improvement of biodiversity – so they could well be considered as qualifying expenditures.

While estimation of costs is based on the best evidence available, it is recognised that the data presented are average figures for both cost and NH_3 reduction and that there will be variability from farm to farm. Research is needed to better understand this variability in order that finance can be directed where it will have the greatest benefit.

Further work is needed to ensure consistency in valuation across a range of health conditions. This work has already started under the UK's COMEAP in work expected to report in early 2024. Discussions from that work have helped inform the valuation work in AMPHoRA.

Chapter 5 Patient and public involvement

Aims

The main aim of AMPHoRA's patient and public involvement and engagement (PPIE) work was to interact with patients and the public as research partners who would bring their different perspectives to help shape and guide the research at all stages. We invited PPIE participations (hereafter, 'community stakeholders') to:

1. inform and strengthen the initial questions that AMPHoRA was asking
2. relate their lived experience and context to researchers' ideas as the project went along
3. critically reflect on the practical implications of different scenarios and policy recommendations, including providing insights on potential concerns and opportunities that emerged as results took shape, and community-derived data to support triangulation and
4. ensure that the communication of scientific data was clear and accessible for different audiences, able to inform the development of locally and nationally relevant policy messages.

Our definition of 'stakeholder' was 'any individual, group or organisation that has an *interest* in, is *affected* by or can *influence* AMPHoRA, positively or negatively'. We framed our PPIE as an opportunity for social learning among patients, the public and all other stakeholder groups, such as agency and not-for-profit partners. We aimed to work with the following stakeholder groups involved in the links between atmospheric air pollution, public health and the environment:

- patients and the public
- policy-makers and regulators
- producers and sellers
- health professionals
- food and environmental change advocates, including third-sector organisations
- AMPHoRA researchers and other collaborators in the research community, including our sister project, AIM-HEALTH (Effectiveness of agricultural interventions to minimise the health impacts of air pollution).

Methods

The backbone of our original proposed methodology was a series of face-to-face stakeholder engagement activities that would bring together community stakeholders from the four UK nations at key stages of the AMPHoRA project. Unfortunately, the COVID pandemic and resulting lockdowns coincided with the 2020 start of AMPHoRA, requiring us to redesign our PPIE methods from scratch to accommodate the impossibility of in-person gatherings. This continued to limit PPIE activities until the final few months of the project in 2023, when we were able to hold our first and only face-to-face meeting of researchers and agency/community stakeholders.

Despite these constraints, our methodology still drew on participatory action research and participatory appraisal principles. In particular, we sought to:

- keep barriers to access as low as possible as we and our community stakeholders learnt and navigate new technologies
- ensure regular, clear communication so that community stakeholders and AMPHoRA scientists could understand each other and exchange ideas freely and
- maintain a warm, engaging, fun communication style to build rapport with and between participants.

2020–2: remote engagement

Our first step in 2020 was to convene two groups, in addition to AMPHoRA's internal groups:

1. Patients and public from the four nations (we generally referred to these as 'community stakeholder groups').
2. A 'Core Stakeholder Group' comprising government agencies, food and agriculture industry, the public, third-sector organisations and academics, AIM-HEALTH (WP1 convened this group).

We initially used our long-term professional contacts in several organisations to identify individuals who might be willing to form PPIE groups. We called these 'Facilitating Organisations':

- Northern Ireland: British Heart Foundation; Pink Ladies Cancer Charity
- Wales: Aber Food Surplus; PIRC UK
- Scotland: Machars and Cree Valley Climate Action Network (MAC-CAN); the 2050 Climate Youth Group; Douglas Ewart High School
- England: Trent & Dove Housing; The Globe Foundation; Living Under One Sun.

These organisations contacted a number of people, most of whom gave permission for us to contact them. We decided against using e-mails, opting for the more personal contact that telephone calls and hand-written letters offered. In an initial phone call to potential volunteers, we explained what AMPHoRA was about and explored their own situation. If they expressed interest in getting involved, we sent them an information leaflet (see *Report Supplementary Material 1*, section 1). In follow-up phone calls, we discussed how they might like to contribute and what they would like to get out of volunteering.

Over the next few months, we secured the interest of 38 people – 8 Northern Ireland (2 men, 6 women), 11 England (1 man, 2 women), 9 Wales (2 men, 7 women) and 10 Scotland (4 men, 6 women). To each of these people, we posted a 'Welcome and Information Pack' consisting of hand-written introductory letters on attractive greetings cards, official welcome letters, consent forms (informed consent, photography, use of quotes), further information about AMPHoRA, a number of first-class stamps, and self-addressed envelopes for returning consents and other communications (see *Report Supplementary Material 1*, sections 2 and 3). We followed up with telephone calls and slowly moved to e-mail contact for those who wished to.

We held a series of online meetings in 2020–2 (see *Report Supplementary Material 1*, section 4 for an example), with phone and e-mail exchanges in between. The order of activities was as follows:

1. Scoping meeting: initial meeting with participants from each nation, to introduce each other, explain the AMPHoRA project in more detail, invite feedback and ideas to improve the research questions, discuss how we could best communicate with one another and begin identifying what they would like the research to achieve from their point of view.
2. Reflection meetings: follow-up meetings with participants from each nation.
3. Research planning meetings: two meetings in which people from two nations came together in one meeting to share ideas. Members of the AMPHoRA research team gave short presentations on planned research activities, joining community stakeholder colleagues in mixed breakout groups to share ideas and discuss the AMPHoRA context from different perspectives, and summarise these in plenary for reporting back to the wider AMPHoRA team.
4. Results discussion meeting: all four nations and members of the AMPHoRA team met to present emerging results and likely scenarios, and to share further reflections on potential concerns, opportunities and communication needs from community stakeholders.

In this way, AMPHoRA researchers were either connecting directly online with patients and the public, or receiving feedback from patient/public groups at all pivotal points in the project.

2023: in-person engagement

Our final 6 months of PPIE were devoted to sharing AMPHoRA results and catalysing conversations around next steps post project. We designed two End of Project (EoP) activities to bring together the outputs from each WP and facilitate

discussions between agency and policy stakeholders, community stakeholders and the AMPHoRA team. These were a 2-day face-to-face workshop in Edinburgh and a 90-minute online webinar, both taking place in June 2023.

Prior to the EoP activities, we held final meetings with our community groups to give people an opportunity to explore the different scenarios that were being finalised, reflect on their relevance and clarity and consider their potential participation in EoP events. Outcomes from these discussions provided final input for the research and modelling efforts. Three of these were face-to-face [England (2 × 2 hours); Northern Ireland (2 days of meetings with groups of patients, participatory activities and 1 : 1 discussions); Scotland (several small group and 1 : 1 meetings)].

Thirty-three people attended the Edinburgh workshop (8 community stakeholders), and 22 people took part in the online webinar (3 community stakeholders; please see *Report Supplementary Material 1*, section 5). In order to facilitate interactive, data-rich sessions with a diversity of lay people, including patients and youth groups, we focused the EoP workshop on three questions:

Q1. Where did AMPHoRA come from, and why was AMPHoRA asking those questions?
Q2. Where are we now? What questions have we been able to answer, and what do those answers mean? What are the implications?
Q3. Where do we go from here? Actions we will now take.

We discussed Q1 in a plenary discussion before facilitating Q2 via a poster exhibition of project research areas and what we termed a 'Gallery Walk'. This was an opportunity for attendees to review and discuss each poster in turn as they walked around with the project team. For Q3, participants were split into four groups, each with a random mix of community and agency stakeholders, and AMPHoRA team members. Through a 'carousel' technique, people had the opportunity to build on each other's ideas concerning AMPHoRA's research outcomes. This was achieved by spending 15 minutes at one of four 'stations' before moving on to the next. Each station had a different theme to structure the implications of AMPHoRA's research and potential next steps. The themes at the first three stations were based on the acronym 'STEEPL' (Social, Technical, Environmental, Economic, Political and Legal), with the fourth station focused on 'Blue Skies Thinking'.

At all stages of the PPIE process, we followed due diligence with respect to data protection, ethical considerations and participant consent in line with NIHR guidelines.

Study results

Positive outcomes from PPIE efforts informed the development, delivery and use of AMPHoRA project science arose in four thematic areas:

1. maintaining a focus on action and applied results
2. prioritising the connections among the AMPHoRA WPs
3. reframing 'involving' the public and patients, to a focus on research 'partnership' with them
4. developing ideas that could inform the design of future projects

Maintaining a focus on action and applied results
The main positive result from the PPIE in this study was the way in which community stakeholders and AMPHoRA researchers were able to build a supportive, powerful approach to collaboration that was relevant for the research and empowering for the people involved. By the EoP workshop in Edinburgh, when people finally met face to face for the first time (including many AMPHoRA team members), people reported feeling like everyone was on the same team. Mutual trust, positive relationships and connectedness enabled considerable progress in refining the research outputs, relating these to potential policy recommendations, ideas for action in real-world contexts, and approaches to dissemination and follow-up. See *Box 1* for data from the Edinburgh EoP workshop that supports this theme.

BOX 1 Examples of participant feedback on AMPHoRA's focus on applied results

'I am impressed with the breadth and depth breath of the work undertaken by the specialists and how it has all been brought together. And it has been a privilege to have the opportunity for the voices of non-professionals heard'.

'I felt included throughout the process and positive that the project is making an impact'.

'The event itself has given me, personally, confidence that ordinary citizens do have agency – we just need to grow the grass roots movement and more quickly as possible'.

'As a community organisation representative, it has been tremendously useful to be part of the AMPHoRA project'.

Communications, reports and dissemination ideas from the workshop were all finalised after high-quality communications between researchers and the public. As a result, all projects were in plain English with many visual presentations, and explained in a way that PPIE group members could communicate them to their own organisations and communities.

Prioritising the connections among the AMPHoRA work packages
A second positive result of PPIE was the community stakeholders' regular emphasis on understanding the interconnections between atmospheric pollution, on-farm changes, dietary changes, public health impacts and cost–benefits of decision-making. AMPHoRA was designed to address the complexity of the research landscape, a complexity given a practical focus through PPIE. Community stakeholders helped support the connections between the WPs, and interrogated AMPHoRA's social, environmental and policy context with their reflections and questions, asking big questions and bringing a sense of shared endeavour. See *Box 2* and *Report Supplementary Material 1*, section 6 for examples of big-picture thinking provided by community stakeholders in initial online meetings. Quotes have been edited slightly for clarity.

Reframing 'involving' the public and patients, to a focus on research 'partnership' with them
A third positive outcome from AMPHoRA's PPIE was the emphasis that community, policy and scientific streams of work were all happening concurrently, and could be interwoven through regular engagement. This was most obviously shown through the EoP activities (see *Box 3*, quotes lightly edited for clarity) but also commented upon by AMPHoRA researchers who participated in early online meetings. Researchers spoke of the value of hearing from community stakeholder about the local projects that were taking place and that could be strengthened by AMPHoRA research. Similarly, community stakeholders appreciated being recognised as active contributors to societal conversations about the connections between public health, agricultural pollution and climate change.

Developing ideas that could inform the design and communication elements of future projects
Finally, PPIE led to strong interest from community stakeholders in taking forward any recommendations from AMPHoRA concerning diet and nutrition that could support healthy lifestyles, with at least three organisations saying that will implement any of AMPHoRA's findings that would add value to their work. Similarly, AMPHoRA researchers identified at least two projects related to nitrogen futures and plant-based school lunches that would be informed by the AMPHoRA PPIE discussions.

BOX 2 Examples of community stakeholder insights on connections between AMPHoRA research areas

'Doctors often see the consequences of air pollution and dietary issues rather late – by the time people arrive in hospital or the GP clinic, the focus is on treatment. Early intervention and prevention are better. For this, we need changes in our diet and food production systems. Type II diabetes and strokes are big problems'.

'Agricultural pollution comes in lots of forms – methane, nitrous oxide, pesticides, insecticides, dust particles, 'direct drill' fertiliser vs. spray fertiliser, water pollution from runoff, ammonia, emissions from transport and refrigeration, smells, and so on'.

'There are lots of things that food 'should/could' be: organic, nutritious, seasonal, sustainable, local, regenerative agriculture, cruelty-free …'

'Diets are contributing to the childhood obesity crisis, but it's hard for deprived (time-poor, money-poor) families'.

BOX 3　Examples of a partnership mindset between AMPHoRA scientists and stakeholders at the end of EoP workshop

'This is a complex issue with many people needed, but opportunity to benefit all society'.

'Feeling a bit emotional to have met so many people who care about these issues and make a difference in their various ways'.

'I'm going to follow up on new contracts – take back to home organization'.

'This is multi-level work; so many places to get involved'.

'Excited to meet so many great people and make new connections'.

'Now we have the science, we need even more engagement with communities'.

'Loved this concept – I'd love to see more projects work like this. There was a coherent story/flow to the Work Packages and heaps of points where the people who the research will impact can get involved and drive the research'.

Our AMPHoRA colleagues also felt empowered by the PPIE process itself, especially the online engagement with the public, and the Edinburgh workshop. Our research colleagues noted that the project was initially designed to inform policy action and to inform people about the often-less-well-known connections between agricultural food production, air pollution and health. For some, the PPIE process enabled the project team to develop a set of policy scenarios that balanced high levels of ambition with practical policy constraints.

In this respect, one colleague noted that

> PPIE activities served as an excellent ground-truthing exercise, helping me and the project team at both strategic and operational levels to relate the planned research to community and stakeholder needs … the team greatly benefited from input from civil society representatives, policy and regulatory stakeholders, both in shaping our research and in formulating the key messages vis-à-vis our outcomes.

Another noted that the PPIE process 'influenced how I delivered the messages to various stakeholders in the final report and will also shape how I do so in the future'.

Other colleagues were conscious of the need to develop a clear narrative for their research area that not only enabled plain English descriptions for patients and the public but also led to increased understanding between the scientific disciplines and WPs, with less 'silo' work in this project than in some others they have worked on. This improvement in communications was elaborated on by another colleague, who stated that

> the engagement helped us to consider and review our communication methods (often we find ourselves just speaking with other scientists), and also gave a great appreciation of the wide variety of 'stakeholders' with an interest in the topics we were covering and the multidisciplinary of the work and of trying to seek solutions. In particular, the potential power of local action groups and support groups to bring about change was highlighted and stressed the need for strong engagement at that level, in addition to our more usual communication pathways through industry or government policy groups.

The process of patient and public involvement and the positive interactions provided insights for some researchers more than others, depending on their WP brief. One colleague noted,

> The PPI engagement provided a useful perspective to gauge the range of awareness and insight into the health effects of air pollution, in general, and then how this knowledge fed into the interactions with agricultural. The interactions highlighted the sizeable gap between public awareness and the specific question of the potential health effects of agricultural emissions, which in many ways mirrored the lack of clarity in the scientific literature in this area. Overall, this emphasises the size for better communication of the complexity of the air pollution mixture, who is exposed to what, and where the health risks may (or may not) lay.

Coming later in the research process, some WPs were struck by how complex messages may be seen as mixed messages, again feeling that avoiding this was an important element of dissemination, viz.:

> *PPI activities, especially stakeholder workshops ... revealed that some stakeholders, such as consumers and local citizens groups, are very keen on changing their behaviours (eating habits) for the environment and health. The impacts of our science messages for them were tremendous. Uncertainties around the main message proved difficult to communicate clearly. We, as scientists, need to be cautious not to give mixed messages and the PPI process helped us to clarify how to do this.*

Limitations

Despite these strengths, there were some limitations to the AMPHoRA PPIE efforts. The main downside of the PPIE effort was the limited diversity in the community stakeholder groups. Despite several attempts, it proved not possible to bring several groups into the research. In particular, we were in regular contact with a youth group at a Scottish high school, and a diverse group of residents in north London who wish to be involved. However, due to COVID, people had no time to do so, because the school had to catch up with the curriculum elements that were lost, and the community group had to focus on maintenance and fundraising issues for their own organisation.

The dissemination and outreach work we have done and our post-project efforts to come will in some way make up for this. Still, our community stakeholder groups had only two minority ethnic people, no one under 24 and most had college education or vocational training. Ironically, the few local people from poorer backgrounds who were involved had to back out after the first meeting because of child care and other responsibilities or because they themselves had hospital treatment to catch up on.

Discussion and conclusions

At regular stages throughout the project, community stakeholders contributed their experiences and ideas related to the core scientific themes of AMPHoRA, namely:

- diet, nutrition and health
- how our food is produced
- agricultural pollution
- climate change and
- the relationships between these things.

The AMPHoRA researchers read community comments and had verbal feedback from the early meetings to inform their scenario modelling. They then shared initial scenarios with community stakeholders for feedback and refinement, and later shared findings from their scenario modelling for additional community stakeholder input.

During several online meetings, researchers had direct communication with community members, allowing questions and answers in real time. In our results discussion meeting, we asked community stakeholders to give presentations about their projects and situations first, so that researchers could respond to them and build on what they said. A real sense of collaboration and shared purpose quickly developed, as researchers worked to craft language and visuals that helped to communicate emerging research results.

Reflections/critical perspective

The two primary challenges for AMPHoRA PPIE related to process and participation. Both of these challenges were exacerbated by the COVID pandemic.

Process: a shift to online engagement

Our planned events were designed to build and maintain positive, effective relationships and high-quality, regular communications. Achieving these things in the absence of normal human contact was our immediate challenge, one that required an entirely different approach based on technologies and capacities that had yet to be learnt by us and by those whose engagement we were seeking.

The consequences were immediate and lasted the life of the project. All meetings had to be held online via a computer or with 'smart' devices. For over 2 years, the only people able to participate in group meetings were those who had access to these, with the confidence and skills to use Zoom (Zoom Video Communications, San Jose, CA, USA) or mobile technology. This had to include training and support for community stakeholders who were less confident using these technologies. We, therefore, lost the fun, creative and powerful methodologies that relied on in-person contact, movement and the part structured, part organic processes of successful group work. We even lost one of the most critical components of any successful project – a powerful, energy-building, relationship-building inception workshop. All these things had rapidly to be moved to virtual events with an almost complete redesign of our process.

It was crucial at the outset of the PPIE to be mindful of the needs of stakeholders who may not be used to digital work, whose internet speeds may be poor, and for whom this medium might raise special concerns regarding their 'on-screen' appearance and issues of confidentiality. We addressed this through supportive 1 : 1 discussions, training and using engaging methods that brought some fun into activities. In a sense, because everything was so new with digital consultation and meetings, we had to 'do it before we could develop it'.

Participation: under-representation from marginalised groups

The people involved in AMPHoRA's PPIE were aged early 20s to late 70s, with a variety of backgrounds, interests and health/disability issues. We were unable, however, to recruit a sufficiently diverse group with regard to age or ethnicity. Only two of our community stakeholders came from minority ethnic backgrounds.

The COVID restrictions with respect to youth engagement and wider recruitment of ethnic minority groups and low-income groups meant that people from those communities were overwhelmed and unable to take on additional engagement in a project like AMPHoRA. Several schools and youth groups who wished to be involved were still playing catch-up with their own regular schoolwork even as AMPHoRA ended.

We had hoped that taking a more dispersed approach, conducting socially distanced focus groups in each nation, would enable us to work through local leaders and facilitators to increase the number of patients and community members we could involve in AMPHoRA. Unhappily, this was not to be. By this time, there was a degree of Zoom fatigue on the part of all community stakeholders, added to which their own local initiatives and normal lives had resumed post pandemic. People felt unable to commit the time as post-COVID work and personal demands increased, adding to the bias towards people who did not have other responsibilities and were busy 'doing'. A further challenge was the loss of half a dozen participants from the focus groups due to changes in their own circumstances. Some could not attend meetings because of work, child care or other responsibilities but were able to give feedback on the scenarios via e-mail or telephone after the meetings.

The people were involved, though, actively engaging with the research, adding rich contextual data, outlining the contexts and conditions in their communities and workplaces and ensuring that the research was grounded in practical realities facing them. Many were active volunteers in their own communities and shared their own efforts in public health, environmental, and food and diet goals. These exchanges provided AMPHoRA colleagues with clearer understandings of how different environmental and social policies are received in rural and urban settings across the UK, reflection on the modelling and other research outputs, and the build-up to the final Gallery Walk engagement and dissemination event. Additionally, one member of the WP6 team works often in Africa and has discussed AMPHoRA with colleagues there who expressed considerable interest in learning from AMPHoRA. We will give a seminar on the project and its findings to staff and students at Egerton University, Kenya, later in 2023, as part of expanding post-AMPHoRA activities.

Chapter 6 Equality, diversity and inclusion

Participant representation

Please refer to *Reflections/critical perspective*.

Reflections on the research team and wider involvement

The UKCEH is the lead institute on the AMPHoRA project with their own equality, diversity and inclusion policy.[84]

The project team were composed of researchers and consultants from across six organisations based in the UK of various sizes and types (university, research organisation, small- and medium-sized consultancies). The project team had a gender split of approximately 44% female and 56% male. The expertise of individuals in the project team covered a range of topics and, when combined, enabled project goals to be met: agricultural sciences; nutrition-health modelling; food and nutrition for global health; environmental epidemiology; cardiovascular effects of air pollution; nutrition and sustainability; atmospheric modelling of APs; atmospheric chemistry and effects; modelling of environmental interventions and their impacts on human health; spatial modelling of atmospheric emissions, concentrations, deposition and effects at national and landscape scales; economic valuation and MCDA; social science, facilitation, stakeholder engagement and PPIE.

This multidisciplinary research team engaged in co-design and codevelopment throughout the research project with both organisational stakeholders, and private citizens, as part of its PPIE approach. The composition of the private citizen group, also referred to as the 'community stakeholder group', had a gender split of about 70% female and 30% male (person numbers for the four nations of the UK are provided in *Reflections/critical perspective*). Despite many efforts, it proved not possible to secure a greater diversity of ethnic groups; other than the two minority ethnic participants, everyone else was of White British/Irish background. Similarly, a majority of citizen stakeholders were over 45 years old. About one-third of the community stakeholders had underlying health issues that were relevant to our study. The group was composed of people working or volunteering in various sectors across the four nations of the UK, for example: charity groups covering local issues (food production and waste, environmental protection, climate change, community hubs) and national issues (health); teachers (secondary school), doctors [general practitioner (GP)], animal welfare (veterinary surgeon) housing associations and environmental community interest company.

Chapter 7　Impact and learning

- Many previous studies of dietary change have focused on the maximum benefits that could be achieved in theory, but which did not focus on specific policies. AMPHoRA modelled the effects of different approaches to reducing meat consumption and was thus able to determine which of these would meet targets for health and the environment simultaneously.
- Other work stemming from this integrated approach is looking at individual behaviour change and how people could be persuaded to make these changes to their diets (e.g. the Accelerating Behaviour Change towards Sustainable and Healthy Diets in Europe project funded by the AF Jochnick Foundation).[85]
- Dietary results from AMPHoRA have already been presented to UK stakeholders, including DEFRA, UK Health Security Agency and the Department for Health and Social Care, in order to help inform future food and agricultural policy.
- A range of technical interventions identified for application at UK farms to reduce NH_3 emissions show health benefits greater than their costs. This includes some that can be cost-negative even before accounting for health and environmental benefits, for example, through reducing demand for nitrogenous fertiliser.
- By the end of the project, community stakeholders felt very close to the research questions and the results that AMPHoRA researchers presented, understood the research well and could relate AMPHoRA research outcomes to potential policy and practice. Future research would benefit from engaging relevant community stakeholder groups and regulatory bodies at the identification/design stages of the project cycle. This could help to build a multistakeholder research partnership from the outset, framing the research questions collaboratively in ways that implementers and communities could identify with earlier in the research process.
- The way in which effective cross-disciplinary research and multistakeholder research partnerships can be built is itself a researchable question. A well-facilitated kick-off/inception meeting is fundamental for building team spirit, strengthening the 'how to do' of cross-disciplinary research, gaining buy-in and building a sense of shared responsibility and excitement about each other's efforts. As this kick-off meeting could not be conducted within AMPHoRA in person because of the COVID pandemic, the early-stage collaboration and co-designing of the research as intended did suffer as a consequence of this.
- However, despite this and the loss of two key project team members, our sense of shared endeavour, responsiveness and approaches to collaboration grew as time went on, so that by the time of the final workshop the sense of each WP's contribution was strong and the strength of the original research design really came through.
- Once research questions have been framed, it is important to retain a degree of flexibility in order to address changes either in the research context (e.g. policy changes) and any unintended or emerging issues that research partners want to include (climate change and the biodiversity crisis being perhaps the most relevant for us, and frequently raised by our community stakeholders).
- Further research on WP6's participatory processes – especially (1) enhancing the development and use of virtual (e.g. Zoom) platforms for engaging geographically dispersed groups and (2) refining our gallery-style approach to presenting results and catalysing cross-disciplinary conversations among researchers from different disciplines, agency and community stakeholders.
- Community-based organisations embedded air pollution, agricultural emissions and their efforts regarding food, health, nutrition and climate change into their policy, strategy and practice discussions. Examples include one large housing association stressing these things for their residents' quality of life; one climate change-focused group bringing agricultural air pollution into their discussions; one food-based community organisation, one health charity and a GP focusing on implications of agricultural air pollution for their work.
- The long-term impacts of AMPHoRA could include but are not limited to:
  1. mobilising further local efforts on healthy eating, food and nutrition among those groups that were involved, and their own conversations with broader constituencies
  2. greater understanding of different pollution sources and air quality, and the implications for diet, nutrition and economic input into decision-making
  3. the researchers involved in AMPHoRA feeling more confident about community engagement and cross-disciplinary research.

- We have established follow-up dissemination discussions with one school, one community-based organisation in London, colleagues in Ireland, a housing association in Staffordshire, a climate group in Scotland and colleagues in Kenya – at Egerton University [with a post-graduate student researcher, and with Centre of Excellence in Sustainable Agriculture and Agribusiness Management (https://cesaam.egerton.ac.ke), and in local communities]. AMPHoRA results will be the subject of a seminar which will be facilitated by AMPHoRA PPIE team members at Egerton University in November 2023. The AMPHoRA team intends to explore the potential for transnational collaboration in future research with Kenyan colleagues and communities.

Chapter 8 Implications for decision-makers

The AMPHoRA research was codeveloped with policy stakeholders and key decision-makers through the ongoing engagement throughout the project. Furthermore, through close collaboration with the sister project AIM-HEALTH (https://fundingawards.nihr.ac.uk/award/NIHR129449), as well as applied research into future strategies for managing agricultural nitrogen funded through the JNCC (https://jncc.gov.uk/our-work/nitrogen-futures/), safeguards were met that AMPHoRA assumptions and scenarios were well aligned with existing policy assessments. The scenarios arising from AMPHoRA were harmonised with existing policy scenarios. The integrated assessment of both technical mitigation options in the agricultural sectors, as well as the impact of dietary change on both emissions and health, highlights the importance of such cross-sectoral and interdisciplinary studies to fully investigate the potential and implications of policy decisions beyond a single-issue focus.

The results of the dietary modelling indicate that a tax on meat and dairy coupled with a subsidy on fruits and vegetables would enable the UK to meet its target for reduced meat and dairy consumption and would also have a positive impact on population nutrition.

Supporting consumption of plant-based meat and dairy alternatives would also meet government targets, but would have a less positive impact on nutrition.

Both scenarios would reduce agricultural air pollution and would therefore confer multiple benefits for the UK population, including those in the lowest income brackets.

The precise balance of costs and benefits at specific farms will vary for individual measures, reflecting local conditions such as soil types and the design of existing facilities on farm. Further research to better understand this variability would be beneficial, for example, to enable better targeting of the farms, where investments would yield the greatest benefits. This could be embedded in the design of policy measures with a focus on spatial targeting of interventions to protect sites especially vulnerable to nitrogen deposition impacts, taking into account the socioeconomic dimension as well as ecological and biodiversity considerations based on sound socioecological approaches.

Chapter 9 Research recommendations

1. There is a need for large-scale epidemiological studies, covering both urban and rural populations, to investigate associations between agricultural-derived PM and 'hard clinical outcomes' (e.g. mortality, ICD-coded health conditions). These studies should measure specific PM constituents (e.g. ammonium compounds) and perform source apportionment, as well as consider confounding factors such as non-agricultural AP constituents and other relevant variables (e.g. socioeconomic variables).

2. A further area for future research should be focused on understanding the health model behaviour, including the impacts of major assumptions and to quantify uncertainties using Monte Carlo simulation or similar methods.

3. Regarding dietary scenarios, efforts should be undertaken to improve the understanding of the relationship between a range of food intakes and each health outcome (nutritional epidemiological research).

4. In order to ensure even treatment in the evaluation of different interventions, further work is needed to ensure consistency in valuation across a range of health conditions. This work has already started under the UK's COMEAP in work expected to report in early 2024. Discussions from that work have helped inform the valuation work in AMPHoRA. Further research could explore impacts of specific local policies for dietary change, for example, changes to public procurement by local authorities or schools.

5. While estimation of costs for on-farm reduction in NH_3 emissions is based on the best evidence available, it is recognised that the data presented are average figures for both cost and NH_3 reduction and that there will be variability from farm to farm. Research is needed to better understand this variability in order that finance can be directed where it will have the greatest benefit.

6. In order for dietary change to happen, tax/subsidy schemes need to be well designed, and innovation in food production needs to be carefully targeted. Both areas would benefit from further research. This should include consideration of public behaviour in response to such initiatives, both in terms of willingness to change and what drives it (e.g. the quality and availability of alternatives, and knowledge of recipes for low meat/dairy options) and potential for opposition (e.g. accusations of interference in the private lives of citizens).

7. There is a significant knowledge gap in the process of evaluating interventions which concerns the consequences of dietary change for the agriculture sector. A significant reduction in demand for meat and dairy products, for instance, could have major consequences for UK agriculture. A wide range of outcomes are possible. Reduction in domestic demand could simply lead to an increase in export of meat and dairy goods. At the other extreme, it could cause farmers to switch to alternative crops and take some land out of production, which may affect the viability of some farms. A detailed evaluation of the probability of different outcomes specific to the changes in consumption patterns assessed here was not possible given the range of variables that would affect production. Further research would enable the sector to be better prepared for change, with improved understanding of the range of outcomes that are possible.

8. Related to this is a need for identification of mechanisms through which changes at farms would be financed whether for introducing on-farm NH_3 controls or for responding to changes brought on by dietary change. The extremes range from farmers paying the full cost of measures taken at farms through to government fully subsidising such changes, for example, using funding through green bonds. We note that the measures considered here have benefits for the three main objectives of green bond finance, climate mitigation, pollution reduction and improvement of biodiversity, so they could well be considered as qualifying expenditures.

From a value of information perspective, it is important to ask which of these recommendations will bring the greatest benefit. This is not an easy question to answer, as priorities for any individual will be likely to reflect their own expertise. It can be argued that priority should be given to research that establishes the need for action or refines knowledge of impacts such that actions can be closely and efficiently targeted. It may also be argued that priority should be given to the design of measures, in order to understand what works and what does work so well, and the potential improvement that may be achieved from different courses of action. The time taken for research is also important, particularly at the present time when the climate agenda, in particular, is driving rapid change in some sectors. Taking this into consideration, the following three key recommendations are made:

Given the magnitude of benefits from dietary measures compared to on-farm NH_3 controls, the results of this research suggest that priority in health research should be given to improving the understanding of the relationship between a range of food intakes and each health outcome, over measures that improve knowledge of air pollution effects on health.

Given that health benefits will be a function of policy design, research to see what will most efficiently influence human dietary behaviour is also of high importance.

Given impacts on the agricultural sector, research on the effects of dietary change on the scale envisaged here (noting that this did not extend close to full vegetarianism/veganism) on farmers and agricultural production generally in the UK is also important.

Chapter 10 Conclusions

- The outputs of this study suggest that dietary changes can bring greater human health benefits than reductions in PM exposure related to agricultural NH_3 emissions.
- The impacts of agricultural NH_3 emissions on human health should not be overstated but must be fully justified by the relevant science.
- The impacts of NH_3 emissions on habitat degradation through nitrogen deposition and the importance of agricultural NH_3 emissions to this are well documented, and this study demonstrates the benefits that human dietary changes would have regarding lower emissions (and hence *N* deposition) in addition to the human health benefits.
- Relatively small dietary changes (i.e. not total vegetarianism or veganism but merely reducing meat and dairy eating occasions by a small number per week) could help meet environmental targets and also improve population health.
- The literature review conducted within this study highlighted that health effects of agricultural emissions have not been fully elucidated by the pre-existing research literature.
- Epidemiological studies suggest that exposure to ammonium-derived PM may exert health effects which could increase the risk of mortality and cardiorespiratory morbidity, albeit the data are limited and inconsistent.
- There is a need to better align this evidence with toxicological studies which suggest that (pure) ammonium nitrate and sulfate have only very modest toxicity.
- Innovative methods are needed to assess the relative toxicity of agriculturally derived PM using exposures that more accurately capture the physicochemical composition of real-world emissions than administration of pure ammonium compounds to experimental models. Direct comparisons to other, more well-studied, sources of PM (e.g. urban PM reference materials, diesel exhaust particles) would be valuable.
- Our results of health modelling based on the investigated scenarios suggested health benefits in terms of the number of deaths, incidence and LYs gained, with the greatest benefits predicted for the older age group. Most of these benefits were brought about by predicted changes in dietary factors with a lower contribution from changes in $PM_{2.5}$ exposure. Health benefits of the investigated scenarios showed inequality among household income groups: lower-income groups receive higher health benefits of the investigated scenarios.
- Following from these results, the greatest economic benefits were associated with dietary change. However, benefits linked to changes in NH_3 and GHG emissions were also important.
- Economic analysis indicates that the benefits of most on-farm measures for reducing emissions of NH_3 generate a net benefit, with these benefits boosted by the cobenefit of reduced emissions of GHGs. The margin of benefit over cost for these measures suggests that this observation is robust in the face of the uncertainties that exist.
- A small number of measures were identified as not generating a net benefit even when the benefits of reduced NH_3 and GHGs were combined. However, these account for only a small part (< 20%) of the identified technical potential for emission reductions.
- Given the benefits identified for dietary change, further work is needed to understand its impacts on the agricultural sector to facilitate a smooth and equitable transition.
- Further research is needed on the design of a mixed tax/subsidy approach to encourage dietary change to maximise the efficiency of any pricing signals that are introduced.
- From a PPIE perspective, building and maintaining successful multistakeholder research partnerships should be considered a key element to build into future research collaborations, especially ideas around community-led efforts, community and agency collaboration, engaging minority groups, engaging young people, citizen science and so forth. Achieving this is in itself a research objective that could be embedded into future research.
- Building partnerships based on strengths that are already in place (e.g. what community stakeholders are already doing) is not only courteous and respectful – it works!
- The issues that AMPHoRA researched were very important for community groups and individuals involved in our research partnership.

Additional information

CRediT contribution statement

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Acknowledgements

Data-sharing statement

Requests for data generated from AMPHoRA should be sent to the corresponding author, Stefan Reis (srei@ceh.ac.uk).

Ethics statement

Ethics approval to conduct this research was received from Reading Independent Ethics Committee on 22 October 2020 (project reference: UKCEH AMPHoRA).

Information governance statement

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Local community stakeholders data: Under the Data Protection legislation, Mind the Gap Training and Research is the Data Controller, and you can find out more about how we handle personal data, including how to exercise your individual rights by contacting: Dr Scott Jones co-director of Mind the Gap Training and Research at scott@mind-the-gap.net; 07799118454; Barholm Enterprise Centre, St John St, Creetown, DG8 7JE, Scotland.

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Disclosure of interests

Full disclosure of interests: Completed ICMJE forms for all authors, including all related interests, are available in the toolkit on the NIHR Journals Library report publication page at https://doi.org/10.3310/GJSR2325.

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Mark Miller declares roles on the committees of the Medical Effects of Air Pollution and the World Heart Federation Air Pollution Expert Group; and consultancy fees for Friends of the Earth Northern Ireland. James Milner declares consulting fees received from the C40 Climate Leadership Group.

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Pastorino S, Cornelsen L, Cuevas Garcia-Dorado S, Dangour AD, Milner J, Milojevic A, *et al*. The future of meat and dairy consumption in the UK: exploring different policy scenarios to meet net zero targets and improve population health. *Glob Sustain* 2023;**6**:1–24. https://doi.org/10.1017/sus.2023.9

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Appendix 1 List of search terms used in the systematic scoping review of the literature on agricultural air pollutants and health

1.　exp Heart Infarction/
2.　coronary thrombosis.mp. or exp Coronary Artery Thrombosis/
3.　cardiovascular disease.mp.
4.　acute coronary.mp.
5.　Myocardial infarct$.mp.
6.　heart infarct:.mp.
7.　acs.mp.
8.　ami.mp.
9.　(coronary adj3 syndrome$).mp.
10.　brain infarction/or brain stem infarction/or cerebellum infarction/or exp brain ischemia/or carotid artery disease/or exp carotid artery obstruction/or cerebral artery disease/or exp cerebrovascular accident/or exp occlusive cerebrovascular disease/or stroke patient/
11.　Chronic Obstructive Lung Disease/
12.　Emphysema/
13.　exp Lung Emphysema/
14.　Chronic Bronchitis/
15.　(obstruct$ adj3 (lung$ or respirat$ or pulmonar$) adj3 disease$).mp.
16.　Bronchiti$.mp.
17.　emphysema$.mp.
18.　(chronic adj5 obstruct$).mp.
19.　(pulmonar$ or lung$ or airway$ or airflow$ or bronch$ or respirat$).mp.
20.　(COPD or COAD).mp.
21.　AECB.mp.
22.　exp *asthma/
23.　asthma?.ti,ab,kw.
24.　exp Pneumonia/
25.　(pneumon* or bronchopneumon* or pleuropneumon*).tw.
26.　bronchitis/or exp bronchiolitis/
27.　(bronchiolit* or acute bronchit* or wheez*).tw.
28.　Respiratory Syncytial Virus Infections/
29.　respiratory syncytial viruses/or respiratory syncytial virus, human/
30.　(respiratory syncytial virus* or rsv).tw.
31.　exp Haemophilus influenzae/
32.　Streptococcus pneumoniae/
33.　Staphylococcus aureus/
34.　(streptococc* or staphylococc* or haemophilus influenzae).tw.
35.　((lung or pulmonary) adj2 (inflamm* or infect*)).tw.
36.　exp mortality/
37.　(mortality or mortaliti*).tw,ot.
38.　exp lung cancer/
39.　(pulmonar$ or lung$ or airway$ or airflow$ or bronch$ or respirat$).mp.
40.　(cancer$ or neoplasm$ or tumour$ or tumour$).mp.
41.　1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27 or 28 or 29 or 30 or 31 or 32 or 33 or 34 or 35 or 36 or 37 or 38 or 39 or 40
42.　Agriculture.mp. or exp Agriculture/or exp Organic Agriculture/

43. farming.mp.
44. livestock.mp. or exp Livestock/
45. fertilizer.mp. or exp Fertilizers/
46. 42 or 43 or 44 or 45
47. Reactive Nitrogen Species/or reactive nitrogen.mp.
48. secondary inorganic aerosols.mp.
49. atmospheric composition.mp.
50. air pollution.mp. or exp Air Pollution/
51. particulate matter.mp. or exp Particulate Matter/
52. exp Ammonia/or ammonia.mp.
53. ammonium sulphate.mp. or Ammonium Sulfate/
54. ammonium nitrate.mp.
55. black carbon.mp.
56. 47 or 48 or 49 or 50 or 51 or 52 or 53 or 54 or 55
57. 46 and 56
58. 41 and 57

Appendix 2　Inputs to economic analysis

Following the full impact pathway approach defined earlier, which is based on detailed modelling of emissions and quantification of impacts, estimated impacts to health are multiplied by a cost per LY lost to account for mortality and cost per case for morbidity.

- there are three main components to health costs in the UK:
  - costs incurred by the NHS
  - lost productivity in the economy (including the voluntary sector and informal care providers)
  - lost utility from pain and suffering, and an inability to undertake normal activities.

Care costs can be calculated from NHS data, while lost productivity is quantified using data on worker output. Lost utility is valued more subjectively using survey techniques. There is some debate as to the additivity of these categories, given that people responding to surveys designed to establish loss of utility could factor in concerns over healthcare costs and productivity. However, for the UK (and other countries with similar systems for welfare provision), this is here considered unlikely, provided that valuations are based on responses from UK citizens because access to health care is free at the point of service and because of the provision of sickness benefits.

Account has been taken of the ICD codes used above in the health impact assessment (see *Table 3*), informing, for example, assumptions on the severity of illness. This is most important for understanding the nature of the non-cancer effects, and ICD codes are mapped to effect for these in *Table 13*.

A starting point for consideration of values to be used in the study is the work of Ricardo[62] for DEFRA. *Table 14* provides their values, representing the WTP of the public to avoid disease and mortality risks. The list of conditions does not match completely to that quantified in AMPHoRA. Ricardo took no account of healthcare costs but did include productivity losses, though not in a way that permits extraction of costs by condition.

TABLE 13 Translation of ICD-10 codes to diseases

T2DM	
E11	Diabetes mellitus with coma, with ketoacidosis, with complications (excluding renal) and without complications
I61	Intracerebral haemorrhage
I62	Other non-traumatic intracranial haemorrhage
I63	Cerebral infarction
IHDs	
I20	Angina pectoris
I21	Acute myocardial infarction
I22	Subsequent myocardial infarction occurring within 4 weeks of onset of a previous infarction
I23	Certain current complications following acute myocardial infarction, including haemopericardium, atrial or ventricular septal defect, rupture of cardiac wall/chordae tendineae/papillary muscle, thrombosis of atrium, etc.
I24	Other acute IHDs, including coronary thrombosis not resulting in myocardial infarction, Dressler syndrome, etc.
I25	Chronic IHD, including atherosclerotic heart disease, aneurysm of heart or coronary artery, ischaemic cardiomyopathy, etc.

TABLE 13 Translation of ICD-10 codes to diseases (*continued*)

Ischaemic stroke	
G45	Transient cerebral ischaemic attacks and related syndromes
G46	Vascular syndromes of brain in cerebrovascular diseases
I65	Occlusion and stenosis of precerebral arteries, not resulting in cerebral infarction
I66	Occlusion and stenosis of cerebral arteries, not resulting in cerebral infarction
I67	(Partial) other cerebrovascular diseases
I68	(Partial) cerebrovascular disorders in diseases classified elsewhere
I69	(Partial) sequelae of cerebrovascular disease
Haemorrhagic stroke	
I60	Subarachnoid haemorrhage
I61	Intracerebral haemorrhage
I62	Other non-traumatic intracranial haemorrhage
I63	Cerebral infarction
LRIs	
J09	Influenza due to identified zoonotic or pandemic influenza virus
J10	Influenza due to identified seasonal influenza virus
J11	Influenza, virus not identified
J12	Viral pneumonia, not elsewhere classified (adenoviral, parainfluenza, etc.)
J13	Pneumonia due to Streptococcus pneumoniae
J14	Pneumonia due to Haemophilus influenzae
J15	Bacterial pneumonia, not elsewhere classified (Klebsiella, Pseudomonas. Staphylococcus, Streptococcus, E. Coli, etc.)
J16	Pneumonia due to other infectious organisms, not elsewhere classified (chlamydial, etc.)
J17	Pneumonia in diseases classified elsewhere (viral diseases, bacterial diseases, mycoses, parasitic diseases, etc.)
J18	Pneumonia, organism unspecified (bronchopneumonia, lobar pneumonia, etc.)
J20	Acute bronchitis due to Mycoplasma pneumoniae, Haemophilus influenzae, streptococcus and various other viruses
J21	Acute bronchiolitis due to respiratory syncytial virus, human metapneumovirus and other specified and unspecified organisms
J22	Unspecified acute LRI
COPD	
J40	Bronchitis, not specified as acute or chronic (adults only: in children to be reclassified to J20)
J41	Simple and mucopurulent chronic bronchitis
J42	Unspecified chronic bronchitis
J43	Emphysema, including McLeod Syndrome, panlobular emphysema, centrilobular emphysema, other emphysemas
J44	Other COPD
J45	Asthma, including allergic and non-allergic asthma
J46	Status asthmaticus (acute severe asthma)
J47	Bronchiectasis

TABLE 14 Costs for loss of utility for various diseases identified from the literature for health impacts, 2022 prices

	Central (£)	Low (£)	High (£)
Mortality			
LYs lost	51,000	38,000	63,000
Morbidity: incidence			
QALY loss	72,000	36,000	96,000
Lung cancer	56,700	28,350	75,600
Diabetes	210,000	105,000	280,000
IHD	250,000	125,000	333,000
Stroke	357,000	178,500	476,000
Morbidity: prevalence			
COPD	16,700	8350	22,300

Source
Ricardo.[62]

TABLE 15 EuroQol-5 Dimensions weights and duration of disease used by Ricardo (2023)

Disease	EQ-5D weight	Duration	Discounted duration
Chronic bronchitis	0.768	[1]	[1]
Asthma	0.722	23.6 (adults) 36.2 (children)	20.1 (adults) 28.4 (children)
IHD	0.61	9.5	8.93
Stroke	0.63	14.8	13.4
Diabetes	0.66	9.1	8.6
Lung cancer	0.56	1.8	1.79

Note
[1] Ricardo's calculations for chronic bronchitis are based on prevalence rather than incidence, and so duration is not factored into the analysis.

The Ricardo morbidity values are calculated by multiplying the value of a QALY (£72,000) by the EuroQol-5 Dimensions (EQ-5D) utility weight (QALY loss) for each disease from Sullivan et al.[89] and the discounted duration of disease. The QALY loss for chronic bronchitis was taken from Salomon et al.[90] The average years of duration of the disease were calculated using the DisMode II model[91] (The World Health Organisation, Geneva, Switzerland) and estimated based on the years of life with disability (YLD). Data are shown in *Table 15*.

The Ricardo value for lung cancer morbidity is low compared to several other chronic diseases listed in *Table 14* because of the short duration of disease following detection. It is often detected too late for treatment. The same would apply to oesophageal cancer (not quantified by Ricardo but included here) as demonstrated in the low 5-year survival rates for both diseases, both in the region of 17.5% (*Table 16*). This contrasts markedly with breast and PCs, in which both have 5-year survival rates in excess of 80%. Colorectal cancer lies roughly midway between the two sets of cancers. The EQ-5D scores, representing QALYs for those with each disease, indicate lower quality of life for those with oesophageal and lung cancers. The score is highest for breast cancer, with colorectal and PCs having scores midway between the two.

TABLE 16 EuroQol-5 Dimensions scores and 5-year survival rates for the UK for the cancers quantified in this study

	5-year survival rate in UK (%)	EQ-5D score
Oesophageal cancer	17.5	0.560
Lung cancer	17.6	0.560
Colorectal cancer	58.7	0.673
Breast cancer	86.3	0.756
PC	88.0	0.687

Source
Nuffield Trust.[63]

For mortality, the value of a life-year lost (VOLY) adopted here is that used in the Ricardo work (£51,000). This is based on a contingent valuation study by Chilton *et al.*[92] that estimated a VOLY associated with a LY spent in good health at £27,630 and in poor health at £14,280 (2002 prices). This was based on a survey of participants undertaken between November 2002 and January 2003. While it is acknowledged that this work is now very dated, it is still relied upon by UK government departments (and hence is used here), though work to update it is finally underway. Ricardo (2023) applied uplifts to convert to 2022 prices. The annual rate of real gross domestic product (GDP) per capita growth sourced from Department for Transport (DfT)[93] (0.9% per annum over the period) was used to uplift WTP estimates between 2002 and the assessment year of 2022, accounting for assumed increase in WTP as incomes rise. The price base of the VOLY estimates was updated using GDP deflators published by HMT.[94] The VOLY derived in this way of £51,000 as a central estimate is lower than the figure recommended by the Treasury Green Book (£60,000) because the Green Book figure is based on an assumption of 2% growth per year in line with guidance from the Department of Health.[95] The lower figure from Ricardo is considered more appropriate here as it is based on actual growth over the intervening period. No account is taken of healthcare costs in the period leading up to death, as these would naturally be incurred at some future point. No account is taken of loss of productivity given that most deaths will occur in people not active in the workforce, acknowledging that this may create some bias to underestimation.

Morbidity values adopted in AMPHoRA are taken from a wider variety of sources. Valuation data for cancers from recent work by Frontier Economics[65] are presented in *Table 17*.

Most estimates in *Table 17* cover a period of 8 years post diagnosis. An exception concerns QALY loss to morbidity, which does not include years 3–8 post diagnosis, and hence associated results for this element should be considered underestimates.

Treatment costs in primary and secondary health care are lower than earlier results from Laudicella *et al.*,[64] which are provided in the last row of the table for comparison, though higher when social care and other carer costs are added. For this study, the Frontier Economics estimates for treatment costs are preferred, as they are more recent and provide greater granularity. However, the Laudicella results indicate uncertainty in the quantification even for the healthcare element which one may assume to be more robust than quantification of utility and productivity losses.

Quality-adjusted life-year loss through mortality is included in this table for information only, as it is otherwise accounted for in this study for consistency with other mortality estimates. Costs linked to mortality (QALY loss, lost paid productivity, lost unpaid productivity) make up between 62% and 74% of total estimates depending on the cancer.

Unpaid productivity losses (representing the indirect cost of lost productivity from unpaid labour, such as domestic work and volunteering) account for roughly half the cost for lung, bowel and 'all other cancers' but only about 20% for breast cancer and are based on National Institute for Health and Care Excellence (NICE) modelling guidance.[96] The nature of this element of cost is particularly uncertain.

TABLE 17 Valuation data for cancers by incidence (morbidity) or deaths (mortality) (£, 2022 prices)

	Lung	Bowel	Breast	All other cancers
Primary and secondary health care	16,700	28,500	23,000	23,700
Social care	5700	7700	9200	7800
Family and/or carer costs	15,600	17,500	22,700	19,300
Paid productivity loss – morbidity	7400	2900	5000	3800
Paid productivity loss – mortality[a]	33,900	17,300	5900	18,700
Unpaid productivity loss – morbidity[b]	82,500	47,300	34,700	52,700
Unpaid productivity loss – mortality[a,b]	247,000	124,000	31,300	140,000
QALY loss for morbidity[c]	39,000	18,200	26,600	20,700
QALY loss for mortality[a]	199,000	134,000	163,000	131,000
Out-of-pocket expenditure by individuals	620	720	930	820
Total, including unpaid productivity losses[b]	**648,000**	**398,000**	**322,000**	**418,000**
Total less unpaid productivity losses[b]	*318,000*	*227,000*	*256,000*	*225,000*
Total cancer morbidity only (c)	*167,000*	*123,000*	*122,000*	*129,000*
Treatment costs from Laudicella *et al.* (2016)[64]	33,400	50,800	34,800	

a Total for cancer morbidity only (total less mortality-related productivity and QALY losses.
b Totals are shown with and without unpaid productivity losses, given uncertainty in these estimates and their dominance on the results.
c QALY loss for morbidity does not cover years 3–8 post diagnosis.
Source
Adapted from Frontier Economics.[65]

European Chemicals Agency (ECHA)[97] provide an estimate equivalent to £407,000 for WTP to avoid cancer morbidity in a three-country survey covering Czechia, Italy and the UK. The ECHA study considered the following cancer attributes:

- probability of getting cancer within the next 5 years
- probability of survival of 5 years after diagnosis
- effects on everyday activities of having and being treated for cancer
- pain and discomfort from having and being treated for cancer.

The resulting estimate figure from ECHA is substantially higher than the QALY loss to morbidity contained in *Table 17*, by roughly an order of magnitude. Reasons for the difference are not clear but could link to the design of stated preference studies, or inclusion of concern over productivity and healthcare costs by respondents to the ECHA surveys. The Frontier Economics estimate is preferred here, however, as the approach taken is similar to that used for other health end points, as described below, combining an estimate of QALY loss with a value per QALY of £72,000. The final estimates adopted for cancers are therefore as follows (*Table 18*), combining data across categories presented by Frontier Economics, excluding QALY loss to cancer mortality as this is otherwise covered in the AMPHoRA modelling. Ricardo (2023) include an estimate for QALY loss to lung cancer morbidity of £56,700, clearly higher than the £39,600 estimate as shown in *Table 18*, but a similar order of magnitude.

The cancers quantified in this study are linked to the data in *Table 18* as follows:

- lung cancer: lung and oesophageal cancers
- bowel cancer: colorectal cancer
- breast cancer: breast cancer
- all other cancers: prostate cancer.

TABLE 18 Adopted estimates for cancer valuation (£, 2022 prices)

	Lung	Bowel	Breast	All other cancers
Treatment costs	38,000	53,700	54,900	50,800
Paid productivity loss	41,300	20,200	10,900	22,500
Unpaid productivity loss[a]	329,000	171,000	65,900	192,000
QALY loss for morbidity and out-of-pocket expenses	39,600	18,900	27,600	21,500

a Unpaid productivity loss can be included as a sensitivity, given associated uncertainties and their importance to the above figures.

TABLE 19 Costs of COPD in the UK (£, 2022 prices)

	Cost, £/patient/year (vs. prevalence)	Cost, £/patient (vs. incidence)
Treatment costs	430	3820
Maintenance costs	620	5520
Exacerbation costs	910	8100
Cost of adverse events	45	400
Total medical costs	**2010**	**17,800**
Productivity	1150	10,200
QALY (loss of utility)	5350	51,900

Chronic obstructive pulmonary disease costs are based on a detailed report from Asthma + Lung UK[98] and are shown in *Table 19*. The underlying analysis accounts for variability in the severity of COPD among diagnosed sufferers in the UK. Two adjustments have been made to the original data. The cost of adverse events has been reduced to account for health impacts that are related to COPD but are quantified under other end points, notably IHD. The QALY estimate for loss of utility has been increased, applying the recommended value of a QALY from HMT (2022) (£72,000) instead of the figure of £20,000 recommended by NICE. The results shown in the table could be applied directly to estimates of prevalence of COPD. To apply to estimated incidence, it is necessary to estimate the average duration of disease. British Lung Foundation[99] cite prevalence and incidence of 1.2 million and 115,000 diagnosed cases of COPD in the UK for 2012. Accepting COPD as incurable therefore suggests an average 10.4 years duration of illness. Loss of utility is discounted at 1.5% and other costs are discounted at 3.5% over this period, reflecting recommendations from HMT (2022).

Patel *et al.*[66] provide estimates of the costs of strokes on health and social care, unpaid carers and lost productivity (*Table 20*). The original study provides separate estimates for ischaemic and haemorrhagic strokes, but here we apply only the average costs, as the differences in estimates are small. Drawing on information on incidence and prevalence provided by Patel *et al.*, it is estimated that patients survive on average 8.3 years following a stroke. This estimate is used to generate the total cost per case (as 'Cost in Year 1' + 7.3 × 'cost in subsequent year') discounted at 3.5% in line with HMT (2022).

Ricardo[62] provides a central estimate for loss of utility from stroke of £357,000 by combining a QALY loss of 0.37 from Sullivan *et al.*[89] with a duration of 13.4 years (discounted) and a value per QALY of £72,000. The same process is followed here, but using a lower period for longevity after stroke of 8.3 years (in line with the calculations above) and a reduced discount rate of 1.5% (from HMT applicable specifically to health impacts), leading to an estimate of lost utility per case of £210,000.

TABLE 20 United Kingdom costs of stroke on health and social care, unpaid carers and lost productivity per incident case (£, 2022 prices)

All strokes	Stage	Cost
NHS and Personal Social Services cost	Year 1	21,100
	Subsequent year	9000
	Cost per case	78,500
Unpaid care	Year 1	30,200
	Subsequent year	17,900
	Cost per case	144,000
Productivity	Year 1	1600
	Subsequent year	1800
	Cost per case	13,200

Source
Patel *et al.*[66] and own calculations.

TABLE 21 United Kingdom costs of type 2 diabetes on health and social care, unpaid carers and lost productivity per incident case (£, 2022 prices)

	Annual	Total
T2 treatment costs (direct)	700	6000
T2 complications not covered elsewhere	1300	10,900
T2 productivity losses (direct)	600	5100
T2 productivity losses (complications, not covered elsewhere)	1100	9400

Source
Hex *et al.*[67] and own calculations.

Type 2 diabetes has been estimated to cost the NHS £8.8B per year.[67] Of this figure, about 80% is linked to complications (myocardial infarction, excess inpatient days, kidney failure, neuropathy, stroke, foot ulcers and amputations and diverse other conditions). There is potential for some of these conditions to be double counted with other effects quantified here. Based on data from Hex *et al.*, it is estimated that approximately 50% of complications could be linked to other impacts quantified in this study, and these have been eliminated from consideration to avoid double counting. Results from Hex *et al.* have been converted to estimated costs per case by dividing annual cost of UK prevalence by incidence (*Table 21*).

Ricardo[62] provides a central estimate for loss of utility from T2 diabetes of £222,000 by combining a value per QALY of £72,000 with QALY loss of 0.36 from Sullivan *et al.*[89] with a duration of 8.57 years (discounted) (*Table 22*). This estimate is adopted here. Data on healthcare and productivity costs for IHD are taken from European Heart Network (EHN)[68] (see *Table 22*). Extrapolation from average annual cost per patient to total cost over the duration of the disease uses a discounted estimation of 8.93 years per case (Ricardo, 2023 and *Table 15*).

Ricardo (2016) provides a central estimate for loss of utility from IHD of £250,000 by combining a value per QALY of £72,000 with QALY loss of 0.39 from Sullivan *et al.*[89] with a discounted duration of 8.93 years (see *Table 15*). This estimate is adopted here.

Lower respiratory infections cover a range of acute conditions (see *Table 13*), including influenza, pneumonia, bronchitis and bronchiolitis. Unlike the chronic conditions covered under COPD, these infections typically last for a short period,

TABLE 22 Average healthcare and productivity costs per incident case of IHD (£, 2022 prices)

	Annual (£)	Total (£)
Primary care	81	720
Outpatient care	160	1400
Accident and emergency	55	490
Inpatient care	670	5900
Medications	200	1800
Total health care	1170	10,300
Production losses due to mortality	900	8000
Production losses due to morbidity	370	3300
Informal care	800	7200

Source
Adapted from EHN (2017).[68]

2 or 3 weeks, and recovery occurs in many cases without medical intervention. For some cases, however, hospital admission and intensive treatment is necessary, leading to a broad range of costs per case. Meier *et al.*[100] provide care cost data for a group of 156,000 patients who had ≥ 1 GP episode of acute respiratory infection during the study period. Of this population, 1% were admitted to hospital, some more than once, with a cost to the health service in the order of several thousand pounds per case. However, overall, the average cost of health care per case, covering the spectrum of severity from those attending their GP to those admitted to hospital, was £211 (value updated to 2022 prices). No estimate has been identified for productivity losses for LRIs. Hunt *et al.*[101] reviewed data from stated preference studies for monetising the loss of utility from acute LRIs and acute bronchitis in children, recommending values from Dickie and Messmann[102] equivalent to £160 (1 symptom day avoided) to £370 (24 symptom days avoided) per case (£2022). Given the clear non-linearity in these figures and the fact that symptoms will persist for between several and many days, the upper bound of the range is selected. Given the limited and aged source data for this estimate, uncertainties in this figure are recognised as being high.

Two types of non-health impact have been monetised:

- **Impacts of NH3 emissions on ecosystems.** These are monetised using outputs from analysis by Ricardo[62] for DEFRA, with an estimate of £487 per tonne of NH_3. This estimate covers provisioning services (timber and livestock), regulating services (GHG emissions) and cultural services (recreational fishing and biodiversity). The valuation draws on a limited literature, and it may be questioned whether the results adequately reflect public preference for protection of ecosystems. Uncertainties in the estimates used may therefore be high.
- **Emissions of GHGs.** The approach to valuation of GHG emissions in the UK is described by the Department for Business, Energy & Industrial Strategy (2023).[103] The values used are taken from the Transport Analysis Guidance of DfT (2023)[104] and reproduced in *Table 23*. Unlike the assessment of air pollution effects, these values are not based on the cost of environmental harm but on the marginal cost of abating GHGs. This approach can be supported from the perspective that, given the Net Zero target for climate policy, any change in emission from one source would be countered by an equal (but opposite) change in another source or sources. The aggregate economic impact would thus not be a change in GHG emissions or impacts, but a change in the costs of reaching Net Zero. This position may be criticised on the grounds that the timing of emission changes prior to reaching Net Zero is important. However, given uncertainties in damage cost assessment for GHGs and the lack of agreed damage costs, the abatement cost method is preferred here.

Values of goods in future years are discounted in economic analysis, recognising social time preference to have goods now. Discounting is applied to most goods, such as the costs of pollution controls at 3.5% in the UK, this rate

TABLE 23 Carbon values, £ per tonne of CO_{2e}, 2022 prices

Year	Low	Central	High
2010	108.26	216.53	324.79
2011	109.91	219.83	329.74
2012	111.59	223.17	334.76
2013	113.29	226.57	339.86
2014	115.01	230.02	345.04
2015	116.76	233.53	350.29
2016	118.54	237.08	355.62
2017	120.35	240.69	361.04
2018	122.18	244.36	366.54
2019	124.04	248.08	372.12
2020	125.93	251.86	377.79
2021	128.29	256.58	384.87
2022	130.24	260.49	390.73
2023	132.23	264.45	396.68
2024	134.24	268.48	402.72
2025	136.28	272.57	408.85
2026	138.36	276.72	415.08
2027	140.47	280.93	421.40
2028	142.61	285.21	427.82
2029	144.78	289.55	434.33
2030	146.98	293.96	440.95
2031	149.22	298.44	447.66
2032	151.49	302.99	454.48
2033	153.80	307.60	461.40
2034	156.14	312.28	468.43
2035	158.52	317.04	475.56
2036	160.93	321.87	482.80
2037	163.38	326.77	490.15
2038	165.87	331.75	497.62
2039	168.40	336.80	505.20
2040	170.96	341.93	512.89
2041	173.53	347.06	520.58
2042	176.13	352.26	528.39
2043	178.77	357.54	536.32
2044	181.45	362.91	544.36
2045	184.18	368.35	552.53
2046	186.94	373.88	560.82
2047	189.74	379.49	569.23
2048	192.59	385.18	577.77
2049	195.48	390.96	586.43
2050	198.41	396.82	595.23

Source
DfT (2023).

being recommended in the UK Treasury Green Book since 2003.[105] There are some exceptions in the Green Book recommendations. Particularly relevant here is the exception for risks to health and life, for which a discount rate of 1.5% is adopted here, recognising that future growth in income will likely feed through to increased WTP to protect health. These figures are used in aggregation of cost and benefit data to derive NPVs.

An alternative approach (the 'damage cost approach') is specific to the benefits associated with NH_3 reductions and uses estimates of damage per tonne NH_3 emission provided by DEFRA[76] and Ricardo.[62] These sources provide a central damage estimate of £9667 in a range of £3727 to £26,172 per tonne of NH_3 released in the UK. Regional differentiation of costs is not provided on the basis that damage from NH_3 is associated in the DEFRA work with formation of secondary pollutants (ammonium sulfate and ammonium nitrate) that form gradually in the atmosphere downwind of the point at which NH_3 is released. The gradual nature of this process reduces the specificity of damage according to the site of release. It is acknowledged that this is a simplification, which is addressed by the more detailed dispersion calculations employed here. The DEFRA/Ricardo analysis covers a different set of impacts to those addressed in the majority of this work, as follows (*Table 24*).

The use of the simplified damage cost approach in addition to the full impact pathway analysis in this study has the following benefits:

- It demonstrates the magnitude of economic benefits according to alternative assumptions adopted by DEFRA for policy analysis in the UK at the present time.
- It provides sensitivity analysis, illustrating the magnitude of benefits under different assumptions on causality, response functions, valuations and the range of impacts associated with NH_3 emissions.

TABLE 24 Impacts linked to NH_3 emissions addressed in the DEFRA damage costs, 2022 prices

Receptor	Pollutant	Exposure	Effect
Low and central sensitivity cases			
Health	$PM_{2.5}$	Chronic	Mortality
Health	*$PM_{2.5}$*	*Acute*	*Respiratory hospital admissions*
Health	$PM_{2.5}$	All	Productivity
Health	$PM_{2.5}$	Chronic	IHD
Health	$PM_{2.5}$	Chronic	Stroke
Health	$PM_{2.5}$	Chronic	Lung cancer
Health	*$PM_{2.5}$*	*Chronic*	*Asthma in children*
Ecosystems	*NH_3*	*Chronic*	*Biodiversity loss*
High sensitivity case: all of the above plus			
Health	$PM_{2.5}$	Chronic	Diabetes (high sensitivity only)
Health	$PM_{2.5}$	Chronic	Bronchitis in adults (high sensitivity only)
Health	*PM2.5*	*Acute*	*Cardiovascular hospital admissions (high sensitivity only)*

Note
Effects in italics are not directly addressed by AMPHoRA.

Appendix 3 Additional results from the economic analysis

TABLE 25 Annual NH_3 emissions and control costs by scenario, for England, Northern Ireland, Scotland and Wales

	Scenario	England	Northern Ireland	Scotland	Wales
1	Present day (2019)	156.2	31.8	29.1	21.5
2	2019 with current agricultural emission measures removed	179.7	36.1	32.0	23.6
3	Current market trend to 2030	162.5	32.0	29.4	21.6
4	Lower emissions from farms – medium ambition 2030	138.5	28.3	26.3	19.1
5	Lower emissions from farms – high ambition 2030	117.6	24.3	23.3	16.9
6	Human diet trend to 2030 – no export limits	168.9	34.5	32.7	22.7
7	Human diet trend to 2030 – with export limits	166.1	34.0	31.9	21.6
8	Human diet trend to 2050 – no export limits	164.0	33.4	32.0	22.2
9	Human diet trend to 2050 – with export limits	160.1	32.5	30.7	20.8
10	Tax on meat and dairy/promote fruits and vegetables – 2030	147.9	25.9	26.5	17.2
11	Increased meat and dairy alternatives – 2030	142.9	25.0	25.8	16.7
12	Tax on meat and dairy/promote fruits and vegetables – 2050	146.7	28.6	28.1	18.8
13	Increased meat and dairy alternatives – 2050	138.3	25.9	25.1	17.4
14	Medium-ambition combination – 2030	125.6	25.5	25.2	16.7
15	High-ambition combination – 2030	106.1	20.0	21.2	13.7

TABLE 26 Annual control costs for NH_3 by scenario, for England, Northern Ireland, Scotland and Wales (£M)

|	Scenario	England	Northern Ireland	Scotland	Wales
1	Present day (2019)	52.8	11.8	6.2	4.2
2	2019 with current agricultural emission measures removed	0.0	0.0	0.0	0.0
3	Current market trend to 2030	57.4	12.1	6.8	4.4
4	Lower emissions from farms – medium ambition 2030	141.6	26.0	20.0	18.7
5	Lower emissions from farms – high ambition 2030	180.1	37.7	26.0	24.9
6	Human diet trend to 2030 – no export limits	59.7	12.8	7.3	4.5
7	Human diet trend to 2030 – with export limits	59.5	12.7	7.3	4.5
8	Human diet trend to 2050 – no export limits	62.1	12.9	7.5	4.6
9	Human diet trend to 2050 – with export limits	61.8	12.8	7.4	4.5
10	Tax on meat and dairy/promote fruits and vegetables – 2030	46.4	9.5	5.8	3.4
11	Increased meat and dairy alternatives – 2030	48.0	9.6	5.9	3.4
12	Tax on meat and dairy/promote fruits and vegetables – 2050	50.6	10.6	6.3	3.8
13	Increased meat and dairy alternatives – 2050	46.4	9.5	5.7	3.5
14	Medium-ambition combination – 2030	121.5	22.1	18.7	15.8
15	High-ambition combination – 2030	145.5	29.8	22.8	19.1
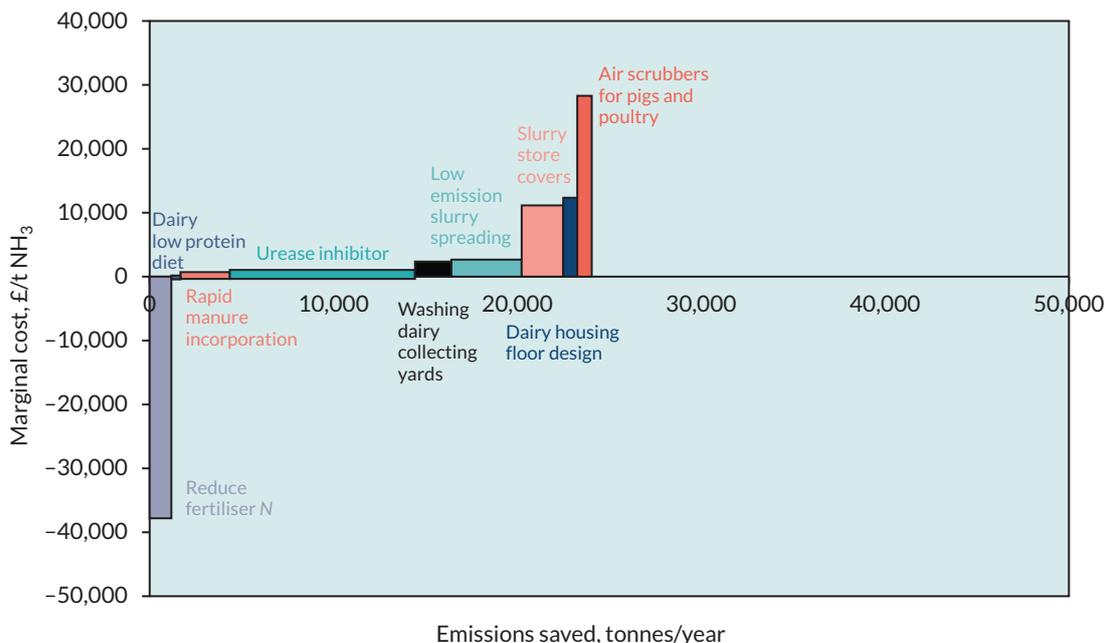
FIGURE 37 Marginal abatement cost curve for NH₃ abatement for scenario 4: 'Lower emissions from farms – medium ambition 2030' for England.
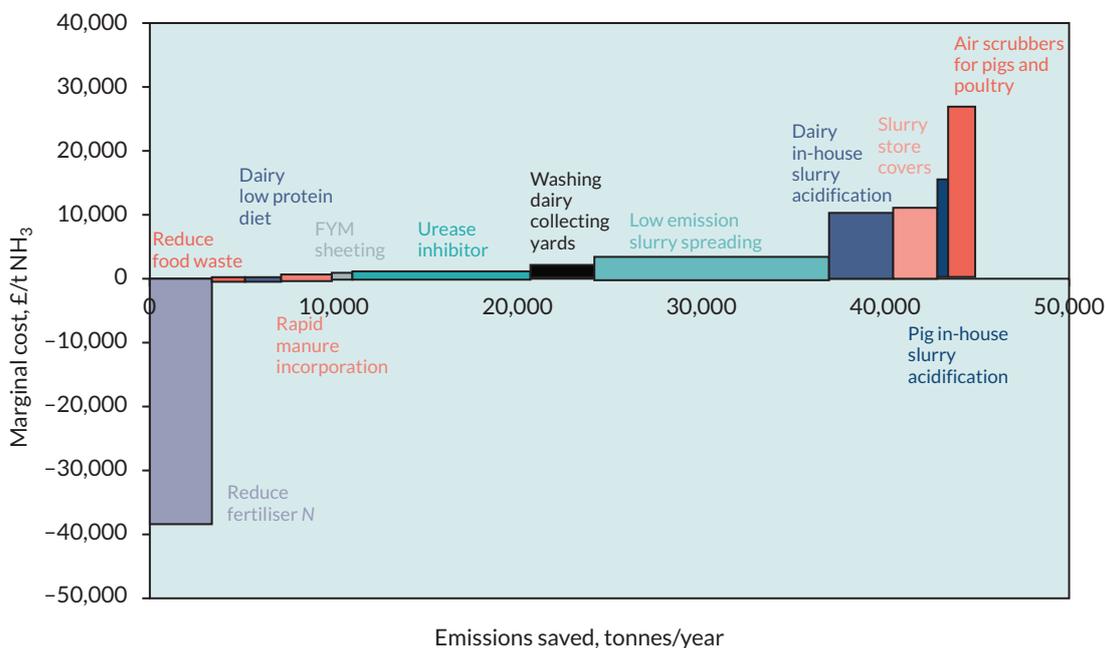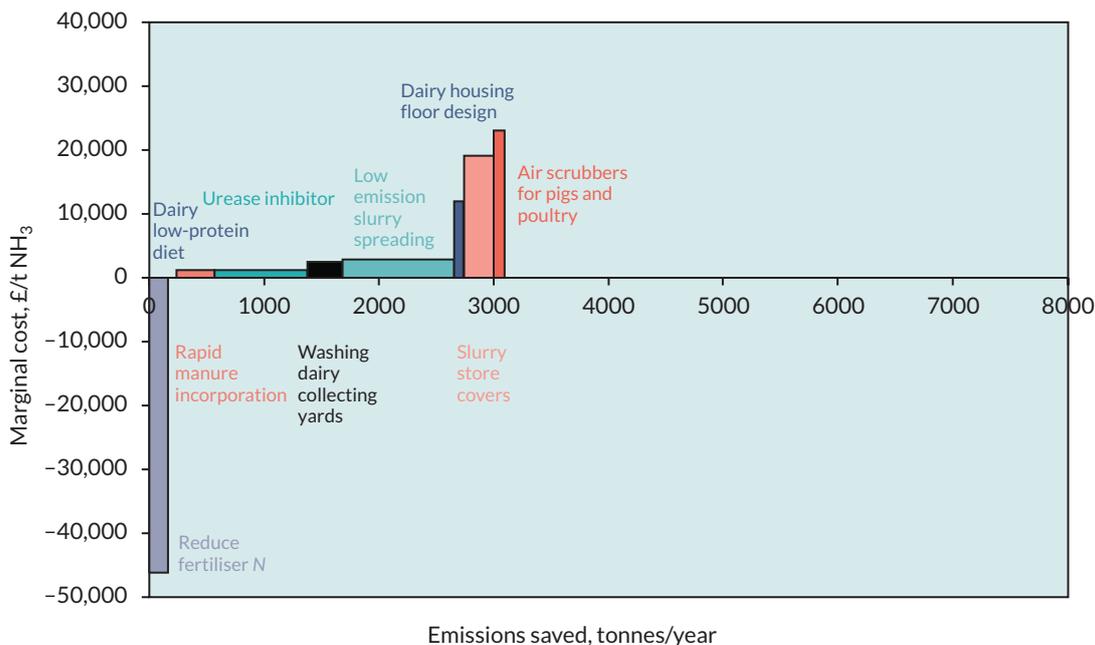

FIGURE 38 Marginal abatement cost curve for NH₃ abatement for scenario 5: 'Lower emissions from farms – high ambition 2030' for England. FYM, Farm Yard Manure.
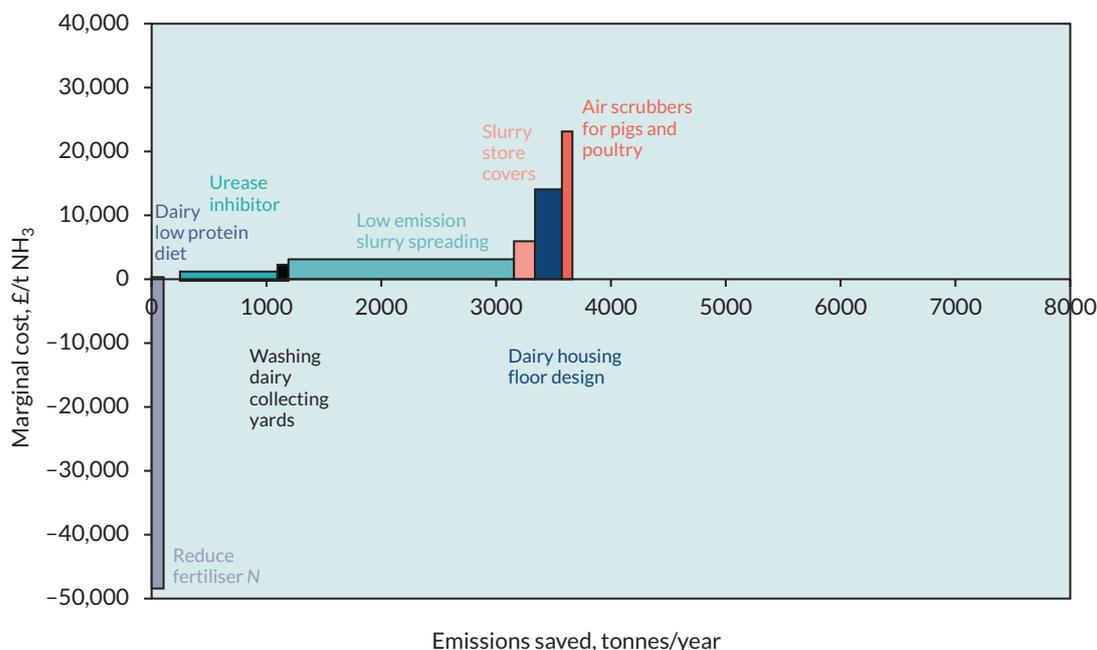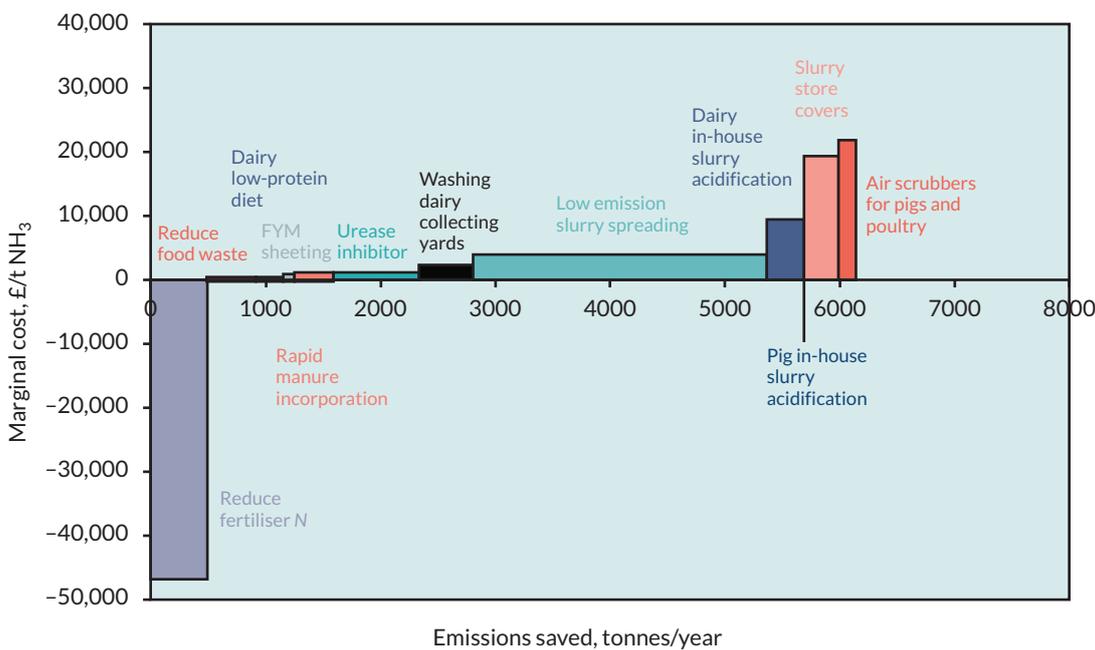
FIGURE 39 Marginal abatement cost curve for NH₃ abatement for scenario 4: 'Lower emissions from farms – medium ambition 2030' for Northern Ireland.
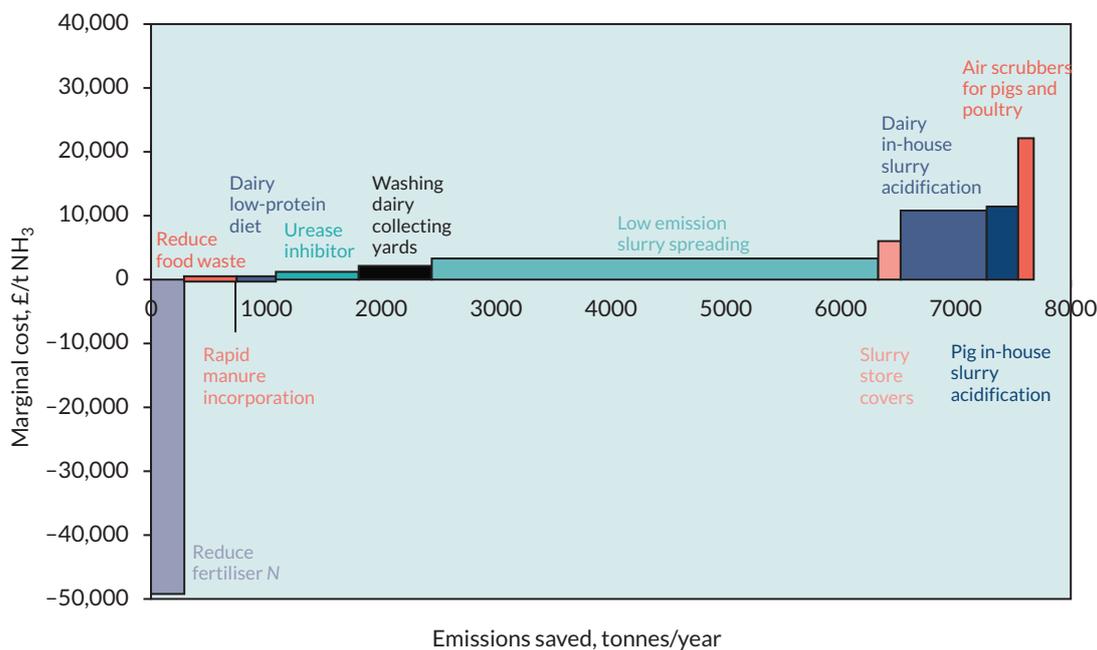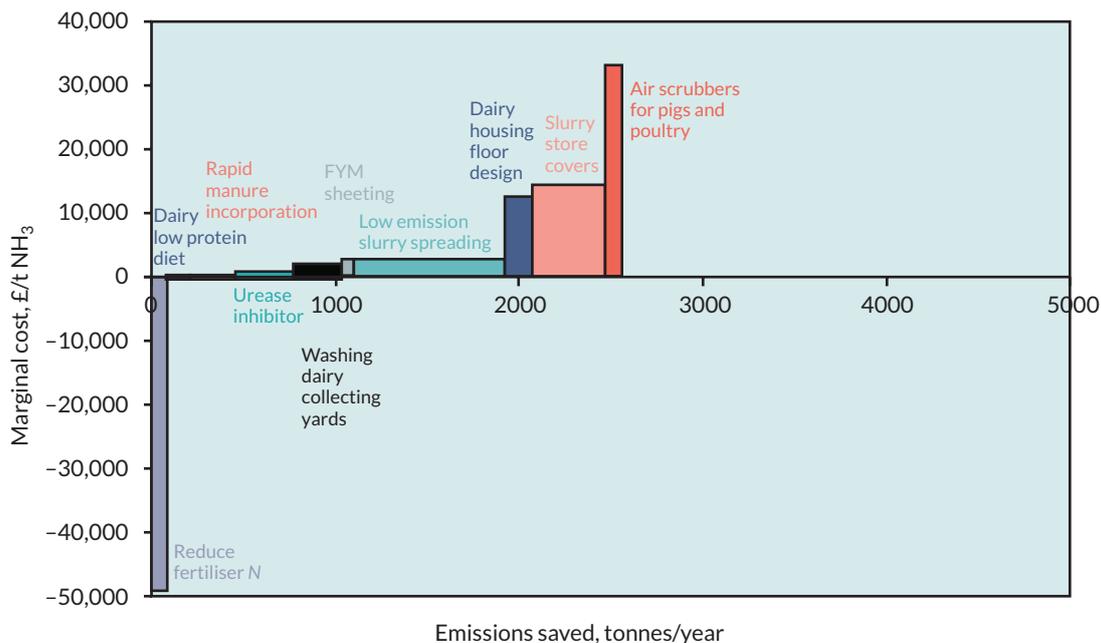

FIGURE 40 Marginal abatement cost curve for NH₃ abatement for scenario 5: 'Lower emissions from farms – high ambition 2030' for Northern Ireland.
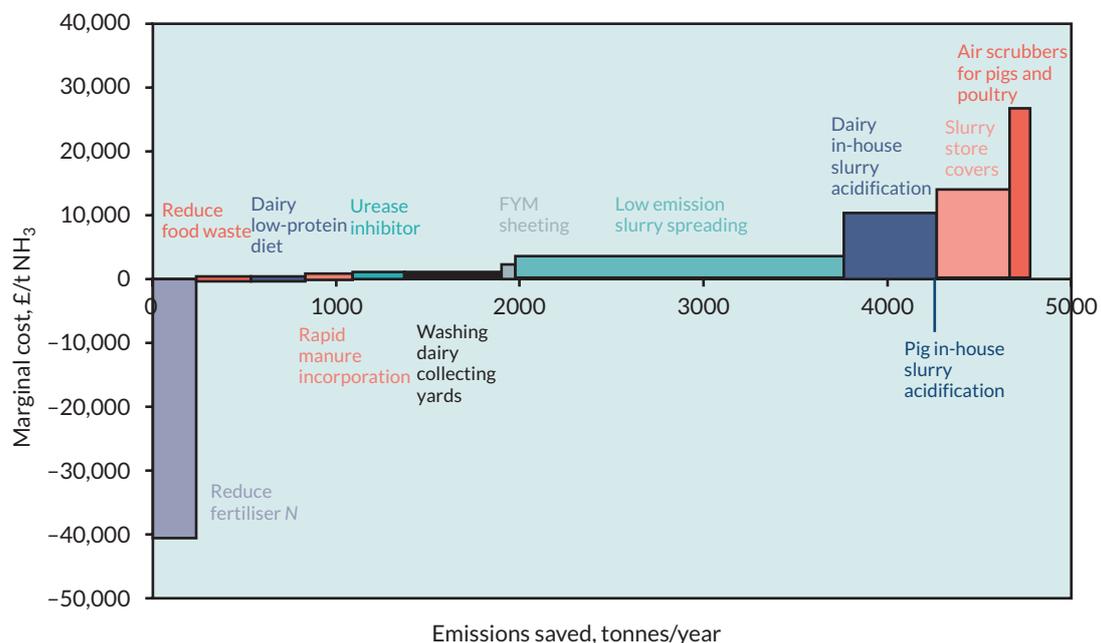
FIGURE 41 Marginal abatement cost curve for NH$_3$ abatement for scenario 4: 'Lower emissions from farms – medium ambition 2030' for Scotland.

FIGURE 42 Marginal abatement cost curve for NH$_3$ abatement for scenario 5: 'Lower emissions from farms – high ambition 2030' for Scotland. FYM, Farm Yard Manure.

FIGURE 43 Marginal abatement cost curve for NH$_3$ abatement for scenario 4: 'Lower emissions from farms – medium ambition 2030' for Wales. FYM, Farm Yard Manure.

FIGURE 44 Marginal abatement cost curve for NH$_3$ abatement for scenario 5: 'Lower emissions from farms – high ambition 2030' for Wales. FYM, Farm Yard Manure.

TABLE 27 Greenhouse gas emissions as kt CO_{2e}/year for scenario 4, 'Lower emissions from farms – medium ambition 2030'

	UK	England	Northern Ireland	Scotland	Wales
Urease inhibitor	41	35	3	3	1
Rapid manure incorporation	26	21	0	2	2
Low emission slurry spreading	27	14	7	3	3
Slurry store covers	−4	−3	0	0	−1
Farm Yard Manure sheeting	0	0	0	0	0
Washing dairy collecting yards	−1	−1	0	0	0
Air scrubbers for pig and poultry	1	0	0	0	0
Dairy housing floor design	0	0	0	0	0
Dairy low-protein diet	21	13	3	3	3
Reduction in N fertiliser use	205	133	20	31	20
Total	**316**	**213**	**33**	**42**	**28**

TABLE 28 Greenhouse gas emissions as kt CO_{2e}/year for scenario 5, 'Lower emissions from farms – high ambition 2030'

	UK	England	Northern Ireland	Scotland	Wales
Food waste reduction	670	379	95	114	82
Urease inhibitor	39	33	2	3	1
Rapid manure incorporation	25	21	0	2	2
Low emission slurry spreading	49	26	12	6	5
Slurry store covers	−4	−3	0	0	−1
Farm Yard Manure sheeting	0	0	0	0	0
Washing dairy collecting yards	0	0	0	0	0
Air scrubbers for pig and poultry	1	1	0	0	0
Pig in-house slurry acidification	0	0	0	0	0
Dairy in-house slurry acidification	3	2	1	0	0
Dairy low-protein diet	47	29	6	6	7
Reduction in N fertiliser use	604	394	60	91	59
Total	**1435**	**882**	**175**	**222**	**156**

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