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REVIEW

Systematic review of reducing population meat consumption to reduce greenhouse gas emissions and obtain health benefits: effectiveness and models assessments

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Abstract
Objectives This review evaluates existing co-benefit models for emission and health outcomes of counterfactual scenarios of reduced meat consumption at a population level.
Methods A novel assessment process was developed, combining selected measures from the Cochrane Review quality assessment tools, from the PRISMA checklist, and model quality measures identified by the authors during the preliminary phases of the review process.
Results Four emission models and three health outcome models have been identified which show great variation in model characteristics and qualities. The estimated counterfactual scenario emission effects presented in the included studies ranged from a reduction of <3–30 % and reduction in the burden of disease ranged from 1 to 16 %. Meta-analysis could not be conducted due to high heterogeneity of model characteristics.
Conclusions All co-benefit studies estimated that reducing population meat consumption could reduce greenhouse gas emissions and the burden of disease. However, important attention must be paid to nutrition balance and a systematic approach in input and output attribute parameters is recommended for better model quality.

Keywords Co-benefits · Meat consumption · Greenhouse gas · Health

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Introduction

Greenhouse gas (GHG) emissions generated by human activities are one of the most important causes of climate change. Climate change has been causing severe damage to people, property, and the environment. Recent studies indicate that the concentration of GHG in the atmosphere is 'increasing at a faster rate than at any other time in recorded history' (EPA 2007). Managing climate change will henceforth be one of the greatest global challenges. To reduce the adverse effects of climate change it has been suggested that developed countries need to cut their emissions by 80–95 % below 1990 levels by 2050 (Eurobarometer 2011; DCCEE 2011; Luers 2007). Livestock production is responsible for a substantial contribution to GHG emissions. McMichael et al. (2007, p. 1259) stated that emissions from agriculture and land use for livestock production are estimated to cause up to 35 % of global greenhouse gas emissions. De Vries and de Boer (2010) examined 25 peer-reviewed studies on assessing the impacts of pork, chicken, beef, milk, and eggs production using life-cycle analysis (LCA). They found the following CO_2 emission rates per kg of meat produced: 3.9–10 kg CO_{2}-e/kg for Pork, 3.7–6.9 kg CO_{2}-e/kg for chicken, 14–32 kg CO_{2}-e/kg for beef.

High meat consumption has also long been blamed for a variety of chronic diseases and deaths. Many studies have shown that dietary intake of fats strongly influence the risk of cardiovascular diseases (CVD) (Hooper et al. 2011; Hu et al. 2001; Jakobsen et al. 2009; Lloyd-Williams et al. 2008; Mozaffarian et al. 2010; WHO 2003). Epidemiological studies investigating associations between meat intake and disease outcomes (Wyness et al. 2011) have linked high meat intake to risk of cancers such as: oesophageal; stomach, lung, endometrial, breast, and especially colorectal. A recent prospective study (Pan et al. 2012) found the pooled hazard ratio (HR) (95 % CI) of total mortality for a 1-serving per-day increase was 1.13 (1.07–1.20) for unprocessed red meat and 1.20 (1.15–1.24) for processed red meat. The corresponding HRs (95 % CIs) were 1.18 (1.13–1.23) and 1.21 (1.13–1.31) for CVD mortality and 1.10 (1.06–1.14) and 1.16 (1.09–1.23) for cancer mortality. Another study (Pan et al. 2011) also found the pooled HR (95 % CI) of type 2 diabetes for a 1-serving/day increase of unprocessed, processed, and total red meat consumption were 1.12 (1.08, 1.16), 1.32 (1.25, 1.40), and 1.14 (1.10, 1.18), respectively. In recent years, a body of co-benefit studies have argued that actions to combat climate change could also yield health benefits (Akhtar et al. 2009; Aston et al. 2012; Audsley et al. 2010; Færgeman 2008; Færgeman and Østergaard 2009; Friel et al. 2009; Gold 2004; Haines 2012; Lindeberg 2012; McMichael et al. 2007; Michaelowa and Dransfeld 2008; Parker 2011; Roberts 2009; Roberts and Stott 2010; Scarborough et al. 2012a; Tukker et al. 2011; Wyness et al. 2011). Here, the term "co-benefit" refers to the collateral health benefits of a GHG emissions mitigation strategy. This paper reports a systematic review of model-based co-benefit studies of reduced meat consumption, with a focus on model qualities, effectiveness of interventions, uncertainties, biases, limitations and heterogeneity.

Methods

Criteria for considering studies for this review

Types of studies

The aim was to review co-benefit studies of meat consumption mitigation strategies with respect to both reduced greenhouse gas emissions and health benefits for a defined study population. Only model-based co-benefit studies of reduced meat consumption in peer-reviewed journal articles and official reports were considered for the review. Studies were included in the review if they focused on both emission and health outcomes of shared scenarios in the same study population (co-benefit); and quantified at least one of the two outcomes: greenhouse gas emissions and human health outcomes directly associated with dietary meat intake.

Literature searching

Systematic searches were conducted according to Cochrane guidelines, for relevant published studies in all fields without any limitation on publication years. The combination of terms used in the search included: "meat" or "livestock", "climate change" or "greenhouse gas" and "disease". The basic search strategy: (meat OR 'livestock') AND ('greenhouse gas' OR 'climate change') AND 'disease', was applied to the following databases: Scopus, PubMed, ScienceDirect and EMBASE and the grey literature databases opensigle.inist.fr, http://www.apa.org/psycextra/ and http://www.ntis.gov/. Electronic searching was also conducted for reports from the websites of The Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Department of Climate Change and Energy Efficiency, the Environmental Protection Authorities of both USA and Australia, the Food and Agriculture Organization of the United Nations, the Intergovernmental Panel on Climate Change, the United Nations Framework Convention on Climate Change, the United Nations Environment Programme and the World Bank. This has ensured that the searches covered all articles which mentioned meat of any type, climate change, greenhouse gas, and any type of disease which might exist in the databases. Abstracts of the identified potential studies were retrieved and screened. Full-texts of the identified potential articles were then retrieved for further analysis. Reference lists of all relevant reports retrieved were screened. Relevant studies identified from the lists have also been located, retrieved, and included in the review.

Types of outcome measures

Two major categories of outcome measure were considered:

1. GHG emission in terms of Metric Tonne Carbon Dioxide Equivalent (Mt CO_2e) and/or percentage change.
2. Meat intake level directly affected health outcomes in terms of morbidity, mortality, life year (LY), disability-adjusted life year (DALY) or quality-adjusted life year (QALY).

Data extraction

For each eligible study, descriptive data on the authors, conflict of interest if applicable, year of publication, objective, study population, study design, method, result, indication of statistical uncertainty of finding, bias and limitations were extracted and investigated.

Assessment of the methodological quality of the included studies

Systematic review assessment tools

Co-benefit studies of reducing meat consumption are studies that involve the specification of a model that represents the proposed pathway of effect between meat consumption and health and greenhouse gas emissions. Published data are synthesized to populate model parameters, supplemented with informed assumptions, where necessary. The models used in the studies are simplification of what is happening and going to happen in reality. The model quality evaluation process aims to assess the appropriateness of the defined model structure, and the extent to which the assumptions input and output data and model structure represent reality.

A list of current well-known systematic review guidelines such as Cochrane Reviews, MOOSE Guidelines, PRISMA and STROBE Guidelines were evaluated. All of them were predominantly developed for primary evidence-based healthcare investigations. They use stringent assessment guidelines to determine if there is conclusive evidence about a specific heath intervention. Consequently, a novel assessment process was developed, combining selected measures from the Cochrane Review quality assessment tools, from the PRISMA checklist, and model quality measures identified by the authors during the preliminary phases of the review process. For each identified model we investigated the following:

1. model purpose,
2. input and output attributes,
3. model type,
4. if the selected model is applicable for the intended use,
5. if the model assumptions are reasonable for estimation of reality,
6. if the model reflects most of the relevant input attributes and their parameters,
7. if the model reflects most of the relevant output attributes and their parameters,
8. input data use and reliability,
9. uncertainties, biases, and limitations indicated in each study, including an assessment of the authors' reported awareness of these factors.

Each study was summarized separately. In-depth analyses of method, methodological quality and study results of the included studies have been conducted.

Assessment of heterogeneity of the included studies

Among the identified models we examined if the input and output data from individual studies could be combined, and whether the identified models could be synthesized to improve outcome estimation qualities.

Summaries of main results

Structured narrative presentation of the results.

Results

Description of studies

All together 377 abstracts were screened. After removing irrelevant reports and duplicates, 351 reports were excluded, 26 full-text study reports were retrieved. An additional 20 full-text reports were identified from other sources. All together 46 full-text reports were retrieved and evaluated. Among them 39 reports did not fully meet the selection criteria and were excluded. Seven reports were included in the review, see Fig. 1.

Included studies

All included studies originated as a discussion of climate change and extended their interest to health impacts (see Table 1). The study of Scarborough et al. (2012a) quantified health outcomes and was an extension of the study from Audsley et al. (2010) and adapted Scarborough et al. (2012b). Therefore, both of Audsley et al. (2010) and Scarborough et al. (2012b) were also partially reviewed.

Methodological quality assessments

Emissions outcome models

Four emission models were identified (see Table 2). All of them were intended to estimate the change in GHG emissions attributable to counterfactual dietary meat consumption reduction scenarios as compared to a population dietary consumption baseline. We identified three basic model input attributes: study population dietary intake pattern as baseline, dietary shift assumptions, and emission factors for the associated food components. All identified models provided the population dietary consumption baseline and estimated the change of emission outcome (EO) as the sum of the product of each of $i = 1, 2, \ldots, n$ dietary change quantities (Q_i) by its emission factor (E_i):

$$\mathrm{EO} = \sum_{i=1}^{n} Q_i \times E_i.$$

The calculations require, Q_i, quantity change food type (i); E_i emission factor for food type (i).

The selected model type was applicable for the intended use of estimating the emission outcome of the included studies. The dietary shift assumptions of both Audsley et al. (2010) and Tukker et al. (2011) reflected most of the potential dietary input attribute parameters, were more reasonable and close to reality (see Table 4). Aston et al.

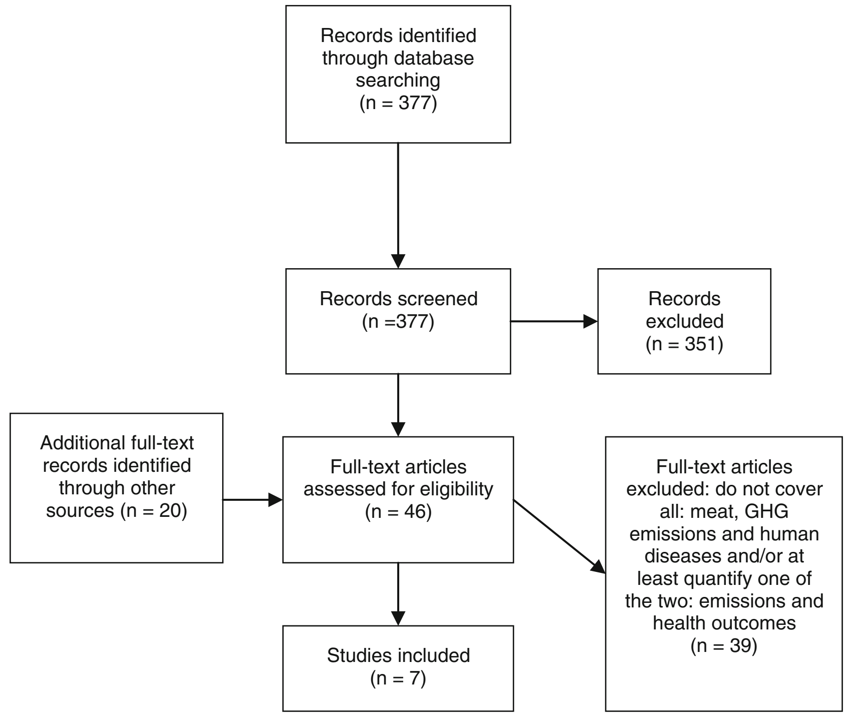

Fig. 1 Literature searching flow chart

Table 1 The included co-benefit studies and selection criteria

Co-benefit studies	Authors	Link meat reduction to GHG emissions reduction	Link meat reduction to human health	Emissions outcome quantification	Health outcomes quantification
Study one	Michaelowa and Dransfeld (2008)	Yes	Yes	Yes	No
Study two	Friel et al. (2009)	Yes	Yes	Yes	Yes
Study three	Audsley et al. (2010)	Yes	No	Yes	No
	Scarborough et al. (2012a)	Yes	Yes	No	Yes
	Scarborough et al. (2012b)	No	Yes	No	Yes, but method only
Study four	Tukker et al. (2011)	Yes	Yes	Yes	No
Study five	Aston et al. (2012)	Yes	Yes	Yes	Yes

(2012) and Michaelowa and Dransfeld (2008) described the effects of reduced meat consumption without consideration of food substitution, which may over simplify the potential of the dietary shift in reality. All models reflected most of the authors' identified input attributes and the consequent emission outcomes as output. However, EO presented in Audsley et al. (2010) and Tukker et al. (2011) have taken all food types of consumption as baseline, whereas Michaelowa and Dransfeld (2008) have taken only meat consumption and Aston et al. (2012) have taken a total of 45 food categories of consumption. Therefore, EOs are incomparable.

All dietary baseline data inputs were nationally representative data from government agents and the best representative data available, hence all were highly reliable. All models took emission factors from life-cycle assessment (LCA). LCA is the main approach for identifying product life cycles' critical control points and summarizing environment impact information. Within the livestock sector, measuring the balance of emissions is complex because they vary with a list of variables such as where they are raised, the type of production system, species, type of soil, climate, inputs to the system, and land degradation, lactation stage and age, animal weight, diet and milk yield (Hartung 2000; Scollan et al. 2010). Measurement could also be made in terms of animals or at a systems level. When measuring at a systems level, the system boundaries must be clearly identified and compared

Table 2 The included models: baselines, assumptions, model types, model inputs and outputs

Studies	Michaelowa and Dransfeld (2008)	Friel et al. (2009)	Audsley et al. (2010)	Tukker et al. (2011)	Aston et al. (2012)
Dietary intake baselines	From national representative data from government agents				
Dietary shift assumptions	Model did not take account of food replacement for meat intake reduction	Model did not take account of food replacement for meat intake reduction	Model took account of food replacements for meat intake reduction and also took account of the effects of changes in import and export volumes	Model took account of food replacements for meat intake reduction and also took account of the effects of changes in import and export volumes; price changes, structural changes in the primary agricultural sectors and the final demand for all food products purchased by final consumers.	Model did not take account of food replacement for meat intake reduction
Emission outcome models					
Model types	Summation of the multiple products of dietary change quantities by emission factors of each dietary food component				
Emission factor Life Cycle Assessment data sources and parameters	Source LCA food database 2003 by the Danish Institute of Agricultural Sciences for meat consumption Parameters Manufacturing, and distribution to slaughterhouse, dairy, bakery, factory and retail, excluding capital goods in the supply-chain	NA	Source Cranfield LCA model, national statistics and process models Parameters Raw materials, manufacturing, and distribution, and retail, consumption, and land use change	Source European Environmentally Extended Input Output (E3IOT) database, the United States CEDA-software Parameters Manufacturing, distribution to consumers and cover the use and disposal phases of products, including capital goods in the supply-chain	Source The UK Department for Environment, Food and Rural Affairs Parameters Raw materials, manufacturing, and distribution to retail, excluding capital goods in the supply-chain
Output emission baseline	Meat consumption only		All food consumption	All food consumption	45 Food categories of consumption
Health outcome models					
Model types		Univariate Comparative Risk Assessment	Multivariate Comparative Risk Assessment		Multivariate Comparative Risk Assessment
Risk factors	NA	Serum cholesterol concentration and saturated fat	Total energy, fruit, vegetables, fibre, total fat, monounsaturated Fatty acids, polyunsaturated fatty acids, saturated fatty acids, trans fats, Dietary cholesterol and salt	NA	Red meat and processed meat
Relative risks of each risk factor		Published high quality meta-analyses	Published high quality meta-analyses		Published high quality meta-analyses
Health outcomes		CHD death and DALY per year	CHD, stroke, cancer deaths delayed or averted per year		CHD, diabetes, colorectal cancer deaths delayed or averted per year

on a like-for-like basis. All emission factors used in each included studies were calculated from different LCA methodologies, and are therefore not comparable. However, all emission factors are from reliable sources and have taken account of the majority of life stages, and so are highly reliable.

It is very important for the authors to be well aware of the uncertainties, biases, and limitations of their studies in order to provide well-informed interpretation of the study results. Table 3, entries 1–9, shows a combined list of nine risks, bias, and limitations from the identified emission outcome models. All of them were applicable to all four identified emission outcome models. Audsley et al. (2010) demonstrated their awareness of them all, Aston et al. (2012) got 67 %, Tukker et al. (2011) 22 %, however, Michaelowa and Dransfeld (2008) showed no awareness at all. Monte Carlo simulation-based 95 % confidence intervals were conducted in Audsley et al. (2010) to test uncertainties of food emission inventories.

Health outcome models

Three health outcome models were identified (see Table 2). All of them were intended to estimate the changes in the burden of disease of the study population attributable to a decrease in exposure to risk factors associated with counterfactual dietary meat consumption reduction scenarios as compared to baseline consumption. We identified four major model input attributes needed for such estimation: study population dietary intake pattern as baseline, dietary shift assumptions, health risk factors, and relative risks of each risk factor for alternative diseases. The health risk factors here could be the dietary components involved or the biological risk factors derived from a specific component, e.g. serum cholesterol concentration and saturated fat from meat. All identified models provided the population dietary consumption baseline and used Comparative Risk Assessment (Truelove and Parks 2012) to estimate the change in health outcome. CRA is the most well-known approach for estimating the burden of disease attributable to changes in exposure distributions and is broadly used. The CRA has been extensively described in the Disease Control Priorities Project (Ezzati et al. 2004, 2006; Hoorn et al. 2004), which assumes that changes in health for each scenario are represented by the difference in modelled exposures when compared with baseline, from which attribute burdens and their relative risks are computed. Therefore, CRA is applicable for the intended use of estimating health outcome in the included studies. It looks at the contribution of each risk factor (univariate approach) to disease or mortality, which is referred to as the population attribute fraction (PAF) and is given by equation:

$$\mathrm{PAF} = \frac{\int_{x_{\min}}^{x_{\max}} R(x)P(x)\,\mathrm{d}x - \int_{x_{\min}}^{x_{\max}} R(x)Q(x)\,\mathrm{d}x}{\int_{x_{\min}}^{x_{\max}} R(x)P(x)\,\mathrm{d}x}$$

where PAF, the fraction of disease or death attributable to changes in exposure distributions.

The calculations require, $R(x)$, The relative risk at exposure level x; $P(x)$, The population distribution of exposure; $Q(x)$, The counterfactual distribution of exposure. Source: Friel et al. (2009).

The combined contribution of multi risk factors (multivariate approach) used in the included studies is given by equation:

$$\mathrm{PAF} = \mathrm{PAF}_1 \times \mathrm{PAF}_2 \times \cdots \times \mathrm{PAF}_n$$

Scarborough et al. (2012a) adapted the dietary intake and dietary shift assumptions from Audsley et al. (2010) which reflected most of the potential dietary input components and biological risk factors derived from the components. Friel et al. (2009), however, have only taken account of serum cholesterol concentration or saturated fat from meat; and Aston et al. (2012) have only taken account of red meat and processed meat (see Tables 2 and 4). Although numerous research reports provided consistent experimental and epidemiological evidence linking meat, and especially red and processed meat, with various cerebrovascular diseases, various cancers, diabetes and mortality (Larsson et al. 2011a, b; McMichael et al. 2007; Micha et al. 2010; Sinha et al. 2009), the health effect of meat intake is not fully understood. Therefore taking meat as a risk factor, as in Aston et al. (2012), may better represent the reality as compared to only taking a biological risk factor derived from meat, as in the study by Friel et al. (2009) or a combination of biological risk factors derived from meat as in the study of Audsley et al. (2010). All relative risks of each risk factor for each disease outcome used in the included models were from different but high-quality meta-analyses. However, none of the models reflected all the identified health outcomes linked to dietary meat intake but a limited selection of outcomes, as indicated in Table 4.

All dietary baseline data inputs comprised the best data available, hence all were highly reliable. All relative risks used in the included models were from high-quality meta-analyses of trials, cohort studies, and case–control studies. However, applying them at a population level could bear a list of uncertainties, biases and limitations. Table 3, entries 1–5 and 10–24, combined a list of 18 risks, biases, and limitations identified from the included studies and 2,

Table 3 The included models: model types, risks, biases and limitations assessments

	Yes, $Y = 1$	No, $N = 1$	NA
General (g)			
1. Indication of uncertainties in actual population dietary shift			
2. Indication of uncertainties of factors and unit measures used in the analysis			
3. Indication of uncertainties of factors and values used for the analysis subjected to change over time.			
4. Indication of uncertainties of outcomes			
5. Identified uncertainties were appropriately subjected to sensitivity analysis			
Emission models (e)			
6. Indication of emission factors have taken account of most of the life cycle stages			
7. Indication of modelling errors for emission factors			
8. Indication of emission factors and indicators were regional specific			
9. Indication of other emission outcomes such as those arising from increased consumption of fruit, vegetables and other possible food replacements			
Health models (h)			
10. Indication of uncertainties in regarding to baseline nutritional quality			
11. Indication of uncertainties associated with assuming log-linear relationships between exposures and health outcomes			
12. Indication of uncertainties in complex multi-nutrients contribution from animal products and their health effects.			
13. Indication of possible implications for other health outcomes			
14. Indication of generalizability of the relative risks in terms of population demographic characteristics			
15. Indication of generalizability of the relative risks in terms of population dietary characteristics			
16. Indication of potential benefits such as those arising from increased consumption of fruit and vegetables.			
17. Indication of possibility of residual confounding associated with meta-analyses of observational studies.			
18. Indication of relative risks obtained from cohort observation studies did not measure the effect of dietary intervention but a comparison of two populations of different meat intake levels. Therefore, the relative risks may not be achieved or it may take time to achieve in natural intervention case.			
19. Indication of not all of the studies included in the meta analyses adjusted their results for each of the dietary factors or biological risk factors that are included in the model			
20. Indication of health outcomes did not take account of the health effects of nutrient deficiencies that may result from a reduction in meat consumption			
21. Indication of an oversimplification that past dietary consumption patterns have no effect on risk of disease might result in some overestimation of the benefits of dietary change.			
22. Indication of the possibility of double counting			
23. Indication of health effects from dietary shift may more effective in some groups than in others.			
24. Indication of effective timeline was not taken in account.			
Subtotal, emission outcomes scores			
Subtotal, health outcomes			
Emission outcomes UBL percentage score $\text{UBL\%} = \frac{\sum(g,Y)+\sum(e,Y)}{9} \times 100$			
Health outcomes UBL percentage score $\text{UBL\%} = \frac{\sum(g,Y)+\sum(h,Y)}{20} \times 100$			
Combined score			

entries 18 and 24, identified by the reviewers which are applicable to all included health outcome models. Scarborough et al. (2012a) demonstrated the best (60 %) awareness, followed by Friel et al. (2009) and Aston et al. (2012) who demonstrated a moderate awareness of 40 %. Both Scarborough et al. (2012a) and Aston et al. (2012) also conducted Monte Carlo simulated 95 % confidence intervals to assess the uncertainties of relative risks. Friel et al. (2009) on the other hand quantified uncertainty by comparing health outcome from exposure to different risk factors and assessed structural parameter uncertainty by repeating calculations, which suggests that their model was

Table 4 The included studies: effects of counterfactual interventions

Michaelowa and Dransfeld (2008)	Scenario, OECD
	A reduction of livestock products consumption in 2002–1990 levels (25 %)
	Emission outcomes, compared to meat consumption only 17 % reduction
Friel et al. (2009)	Scenarios, UK and São Paulo city
	30 % reduction in livestock product consumption by 2030
	Emission outcomes
	Authors assumption: 30 % reduction in livestock production emission,
	Health outcomes
	15 % reduction in UK CHD (2,850 DALYs/million population/year), and
	16 % in São Paulo city (2,180 DALYs/million population/year)
Audsley et al. (2010)	Scenarios, UK
Scarborough et al. (2012a)	Scenario 1, 50 % reduction in livestock product consumption balanced by increases in plant commodities.
	Scenario 2, shift from red meat (beef and lamb) to white meat (pork and poultry). Red meat consumption is reduced by 75 %.
	Scenario 3, 50 % reduction in white meat consumption balanced by increases in plant commodities.
	Emission outcomes (Audsley et al. 2010), compared to all food consumption
	Scenario 1, 19 % reduction
	Scenario 2, 9 % reduction
	Scenario 3, 3 % reduction
	Health outcomes (Scarborough et al. 2012a)
	CHD, stroke or cancer deaths delayed or averted per year
	Scenario 1, 16 %, 36,910 (30,192–43,592)
	Scenario 2, 1 %, 1,999 (1,739–2,389)
	Scenario 3, 4 %, 9,297 (7,288–11,301)
Tukker et al. (2011)	Scenarios, Europe
	Scenario 1, a pattern according to universal dietary recommendations
	Scenario 2, the same pattern with reduced meat consumption
	Scenario 3, a 'Mediterranean' pattern with reduced meat consumption
	Emission outcomes, compared to all food consumption
	Minor reductions of Global Warming and environmental impacts (<3 %)
Aston et al. (2012)	Scenarios, UK
	Divided the population red and processed meat consumption into fifths intake groups, double the population vegetable consumption and all population adopted the lowest fifth of red and processed meat
	Emission outcomes, compared to 45 food categories of consumption
	3 % reduction
	Health outcomes
	Ranged from 3.2 % reduction for diabetes in women to 12.2 % for colorectal cancer deaths delayed or averted per year

robust to parameter uncertainty but less so to structural uncertainty.

Effects of interventions

All co-benefit studies estimated that reducing meat consumption could reduce GHG emissions (ranged <3–30 %) and simultaneously bring in health benefits (reduce selected burden of disease ranged 1–16 %) (see Table 4). The included studies showed that substantial reduction in meat consumption could bring in significant emission benefit in UK but not necessarily in Europe. The most apparent reasons for the differences are differences in dietary shift assumptions and difference in LCA input attribute parameters used in the different studies. Scenarios taking account of plant food substitutes yield less emission benefits. However, such scenarios would be more realistic.

Michaelowa and Dransfeld (2008) assumed a 25 % consumption reduction in livestock products in OECD population in 2002–1990 levels could reduce obesity and bring in 17 % reduction in GHG emission due to livestock products consumption. Friel et al. (2009) also assumed a 30 % reduction in livestock product consumption by 2030 could reduce 15 % coronary heart disease (CHD) in UK and 16 % in São Paulo city and bring in 30 % reduction in GHG emission. Both studies have not taken account of the effects of food substitute or dietary balance issues; or other health outcomes such as stroke, cancer, and diabetes. Therefore, both of them highly overestimated the emission reduction and could underestimate the health benefits of reducing meat consumption in high meat intake individuals. The remaining studies (Aston et al. 2012; Audsley et al. 2010; Scarborough et al. 2012a; Tukker et al. 2011) all accounted for food substitutes, providing a more realistic estimation of the emission and health benefit. Only Tukker et al. (2011) have taken account of healthy dietary recommendations with reduced meat, but the consequent dietary balance issues have not been addressed. Emission outcomes from Audsley et al. (2010) and Tukker et al. (2011) have taken emissions from all food types of consumption as baseline and Aston et al. (2012) have taken 45 food categories of consumption, hence the relative percentage reduction would be smaller (Table 4) than in Michaelowa and Dransfeld (2008) and Friel et al. (2009) which only taken account of emission percentage reduction based on emission from livestock product consumption only. Current identified health benefits of reducing meat intake and replacing with plant food intake include reduced mortality from http://en.wikipedia.org/wiki/Cardiovascular_diseaseCVD, cancers, diabetes, and total mortalities. Aston et al. (2012) quantified effects on CHD, diabetes, and colorectal cancer. Scarborough et al. (2012a) quantified effects on CHD, stroke or cancer. Therefore, both of the studies are more representative of the potential overall health outcomes than the study of Friel et al. (2009) which only quantified the effects on CHD; but still potentially underestimate the overall health benefits of reducing meat consumption.

Heterogeneity of the included studies

Although three of the included studies (Aston et al. 2012; Friel et al. 2009; Scarborough et al. 2012a) modelled counterfactual scenarios of the UK population, they are not comparable due to high heterogeneity of model characteristics. Given that each study population has its unique characteristics and dietary patterns, each study has its unique dietary assumptions and input attribute parameter assumptions, structure, and output parameters. The input output data from the included studies are incomparable and could not be pooled together for meta-analysis. However, all four emission outcome estimations shared the same model type and input attributes, as did the three health outcome estimation models.

Excluded studies

Thirty-nine studies were excluded after assessment of the full text of the articles. The most frequent reasons for their exclusion were that they (a) did not meet the co-benefit criteria of covering both emission and health benefits or (b) did not involve quantification of at least one of the two outcomes, i.e. emission or health.

Discussion

Summary of main results

This review included seven primary studies making five co-benefit assessments. We assessed model quality and the collateral effectiveness of counterfactual scenarios of reduced meat consumption on GHG emissions and the burden of disease. The included studies concluded that reducing meat consumption at population level could potentially reduce emissions and yield health benefits. However, due to variation in the nature of the estimation itself, derived estimates of intervention effectiveness among the included studies also show substantial variation. Such variations were largely due to difference in model assumptions and the represented input and output attribute parameters.

Potential biases in the review process

The comprehensive methods established during this review were designed to reduce potential biases in the review process. The broad coverage of databases and search engines and the combination of terms used for searching in all fields were designed to identify all model-based studies of meat consumption with respect to associated diseases and GHG emission information. The hand-searching also compensated for insufficiencies in the database searches. Studies were selected based on well-defined study criteria to ensure consistency in the selection process. Study characteristics and methodologies were well assessed by multiple reviewers. Therefore, every effort has been made to limit the potential bias and ensure that the review was conducted with integrity.

Limitations of the review

All models in the included studies used a combination of aggregate and structural modelling approaches. Dietary intake patterns, emission factors, or relative risks were important input attributes of the included studies. We assessed the quality of each input attribute based on the reliability/credibility of the data sources and input attributes parameters used in the studies. The input attributes, such as the emission factors used in each of the models, are the sum of a unique combination of life cycle emission attributes in each of the structural LCA models. Limited details of those structural LCA models could be found. In addition, emission inventories of each life cycle stage attribute used by those models, according to Scollan et al. (2010), could have errors of as much as ±30–50 %. In addition, the relative risks for the burden of disease used in the included studies were taken from meta-analyses of a combination of cohort, case–control, and randomized trial studies. The quality and characteristics of the input studies in each meta-analysis would also affect that of the output. We have not examined the nature of the input study attributes used in the selected meta-analyses.

Implications for practice

This review has provided reliable support that reducing meat consumption at population level could simultaneously yield emission and health benefits. However, a list of uncertainties, biases, and limitations identified in Table 3 has not been addressed in the included studies. Furthermore, animal foods are sources of protein, energy, and nutrients—such as iron, calcium, selenium, vitamin B12, zinc, phosphorus, niacin choline, riboflavin and all of the essential amino acids which are important to human well being. None of the included studies has paid specific attention to dietary nutrition balance therefore substantial reduction in meat consumption may lead to mal-nutrition. This is not addressed in any of the included studies. Furthermore, meat production has played an important role in countries like Australia and Mexico. The potential economic and social impacts of substantial reduction in meat consumption at population level should not be neglected. Therefore, Policy makers should be cautious when interpreting the study results in decision making.

Implications for research

Current co-benefit models of reducing meat consumption are high in heterogeneity. Consequently, effectiveness of the proposed meat reduction mitigation strategies could not be compared between different studies. Both emission and health outcomes' modelling strategies presented in the included studies are the most broadly used modelling strategies used in published similar studies. We recommend a systematic approach in dietary shift attributes, LCA parameters, use of relative risk of meat and food components as far as possible and output attributes to address input output deviations and better reflect reality. The list of uncertainties, bias, and limitations identified in this review could provide insight of further technology/research improvement in obtaining the emission inventories and relative risk used in the estimations. Decision makers and researchers can use this review as knowledge baseline to determinate further research needed. Last but not the least, the model quality evaluation tools established in this review and the uncertainties, bias, and limitations raised in this review could be also used as a future study guideline or modified for similar model evaluation work. Current co-benefit models of reducing meat consumption also neglected the dietary balance issues and the consequent health effects. More attention is needed on the study populations' specific dietary patterns and their nutrient need. Emission is a global phenomenon; and population diet, disease patterns, GHG emission factors and even food consumption life-cycle attributes are country specific. Meat production and trade play important roles in global food security and nutrition balance. Current co-benefit studies of meat consumption mainly focus on the UK. More studies are needed across different countries to develop sustainable global meat strategies.

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