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Towards net zero nutrition: The contribution of demand-side change to mitigating UK food emissions

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ABSTRACT

The UK has committed to achieving net zero emissions by 2050, and the food system is increasingly recognised as a critical part of realising this scale of mitigation. Food-related emissions are ultimately driven by demand. We therefore present a scenario analysis of the mitigation potential from transformative demand-side interventions in the UK food system. We construct a hybrid physical input-output food system model, evaluating the effect on emissions of moderating calorific intake to that in the UK Government Dietary Recommendations, modal shifts in diets towards plant-derived proteins, and of reducing consumer food waste. We conclude that the UK could reduce absolute annual territorial Greenhouse Gas (GHG) emissions by 52% (from 2017 to 2050) in the most ambitious scenario, where dietary transitions are the single most effective measure with reductions of 22–44%. Demand-side mitigation is also well positioned to address the UK's consumption-based food emissions, which are approximately 52% higher than current territorial emissions emitted in the UK. Well-designed and equitable policy is required to realise the full mitigation potential of these options, and to navigate multiple structural issues including food poverty and carbon leakage. However, the current culture of acceptability around pro-environmental dietary change in the UK has arguably created greater space for policy intervention on the demand-side. Novelties of the analysis include modelling a range of demand-side options using territorial and consumption-based emissions accounting, designing scenarios of dietary change which reflect recent trends towards sustainable consumption, and proposing up-to-date policy interventions. The implications of the analysis are highly transferable to other developed nations. A demand-side mitigation approach could feasibly implement the identified emissions savings whilst working towards a more environmentally, socially and economically sustainable food system.

1. Introduction

1.1. The UK food system in context

The global food system is a key target for mitigation in a world aiming to limit temperature rise to 1.5 °C above pre-industrial levels. Although global scale estimates of Greenhouse Gas (GHG) emissions from the food system vary, the Intergovernmental Panel on Climate Change (IPCC) identified that 20% of anthropogenic emissions can be attributed to 'agriculture activities within the farm gate and associated land use dynamics' (p. 60, IPCC, 2018). Rising global demand for emissions-intensive food groups (for instance meat and dairy) as a result of greater and growing global affluence are likely to compound this contribution (Springmann et al., 2018; WRI, 2019). Demand for meat and dairy products alone is expected to double globally by 2050 (p. 491, Garnett, 2009).

Debate on the contribution of food systems to the climate crisis is timely in the context of increasingly ambitious mitigation targets. This is particularly with regards to the linkages between planetary and public health as underscored by several high profile reports at the global scale (IPCC, 2018; WRI, 2019), in the UK (House of Commons, 2019), as well as the launch of the EAT-Lancet Commission (2019). In the UK, the Climate Change Committee (CCC) estimates that 11% of territorial UK GHG emissions are attributable to agriculture and land use, and predict that the sector will be a more significant emitter by 2050 (based on 2016 data; p. 12, CCC, 2018). With the legislation of a net zero 2050 target in the UK (Priestley, 2019), underwritten by the Paris Agreement's commitment to 1.5 °C (UNFCCC, 2015), food system change is being recognised as an increasingly important mitigation option.

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Territorial emissions are estimated to account for only a fraction of the total consumption-based impact of UK food at the global scale (Audsley et al., 2010). A territorial emissions accounting approach considers the GHG emissions occurring under a particular national jurisdiction (discounting those emissions occurring from international aviation and shipping; Barrett et al., 2013). By contrast, in a consumption-based accounting approach 'emissions are allocated according to the country of the consumer, usually based on final consumption' (p. 453, Barrett et al., 2013). That is, the consumption-based footprint of the UK's food intake would be the UK's emissions from producing food, subtracting those emissions from exported food products, and adding the emissions from imported goods. Therefore to account for the full international emissions impact or footprint of UK final food demand, it is necessary to use a consumption-based emissions accounting approach, such as multiregional input-output (MRIO) modelling.

The relatively greater consumption-based impact of UK food is understandable in light of the UK's self-sufficiency ratio – a measure of 'food production as a ratio of available supply' (p. 89, Clapp, 2017). In 2017 the UK imported approximately 50% of its food by value, with 30% from Europe (Defra, 2019). Land use change (LUC) emissions represent a substantial additional impact of UK food demand, particularly in the types of LUC driven overseas and their associated opportunity costs. Audsley et al. (p. 64, 2010) find that 40% of embodied food emissions are attributable to 'global land use change pressures'.

Both territorial and consumption-based food emissions are strongly influenced by the composition of food demand. Greater consumption of GHG-intensive food groups such as meat and dairy is positively correlated with affluence, as is often indexed against national Gross Domestic Product (GDP) (Roser and Ritchie, 2019). Indeed, many developed nations consume more meat than is nutritionally required, often to the detriment of health (Godfray et al., 2018). This is manifest in the estimate that average per capita consumption of protein in the US and Canada is 20% over the recommended amount (0.8g per kilogram body weight) (Wilson, 2019). In-keeping with the principle of 'common but differentiated responsibility', affluent nations such as the UK have a responsibility to mitigate GHG emissions further and faster than developing regions, in large part since their supply chains depend on the territorial emissions of such countries.

Whilst food-related GHG emissions are ultimately driven by final demand for products at the consumer level, emissions are produced across the food supply chain. Fig. 1 suggests the flows of emissions from primary production to household consumption, and sources of indirect emissions such as livestock and soil emissions, LUC, and the transport of food. Whilst primary production may be considered the 'starting point' for food emissions, this represents only a share of the cumulative impact of a given food product. Life cycle analyses (LCA) are one method for accounting for the emissions created at each supply chain stage.

The UK food system is at a structural turning point, facing new demands and challenges stemming from demographic, economic and political change. With likely future population growth in the UK, of at least 4.5% between 2018 and 2028 (ONS, 2019) and the noted trend for overconsumption, there is need to re-evaluate the structure of the UK food system. It is possible that the UK could become increasingly reliant on food imports if current trends in declining self-sufficiency continue, and as part of a highly globalised food supply chain (Defra, 2019).

1.2. The importance of demand-side change

Demand-side change should be a critical ongoing focus for food studies, as the ultimate determinant of future food emissions. As Nemecek and Poore note, 'today, and probably into the future, dietary change can deliver environmental benefits on a scale not achievable by producers' (p. 5, 2018). Demand-side change has important benefits in addressing consumption-based emissions by improving resource efficiency and changing both the quantity and structure of demand for imported goods (Owen et al., 2018). Demand-side options impact consumption-based emissions to a greater extent than improving production efficiencies alone, since they act on all food supply irrespective of national origin. Furthermore, demand-side action has an additional public health rationale, where in improving the emissions-intensity of UK diets there is also scope to improve health outcomes. Uniting these two policy objectives provides a cogent argument for demand-side change.

In this analysis we consider the potential contribution of three demand-side mitigation options to achieving net zero food emissions, according to three ambition pathways (business-as-usual, BAU; low ambition; and high ambition). We construct a UK food system model to assess the role of following Government Dietary Recommendations for calorific intake (GDRs), dietary transitions, and reduction in consumer food waste, on both a territorial and consumption basis. The key novelties of the analysis involve the modelling of a range of demand-side options, incorporating recent trends in pro-environmental attitudes to dietary change, and in proposing timely policy interventions to realise the mitigation potentials outlined. Interventions to improving the production efficiency and emissions intensity of food supply are beyond the scope of this analysis, given the emphasis on the potential of demand-side interventions, as measures which are known, available and readily implementable.

A further novelty inheres in the choice of method, by constructing a hybrid physical input-output model to implement the scenarios. MRIO modelling accounts for the environmental impact embodied in the trade of goods and products allocated to the country of final consumption. That is, MRIO 'quanti[fies] the full environmental impact of a product's supply chain [...] consequent on a nations' final demand for goods and services' (p. 633, Owen et al., 2018). This analysis constructs physical scenarios of food demand based on age-weighted per capita nutritional requirements (on a calorific basis), before using MRIO data to translate the scenario assumptions into emissions and evaluate the impact of the scenarios on future UK food footprints. The diet profiles are constructed using seventeen diets in the literature, translated to 69 Classification of Individual Consumption by Purpose (COICOP) food categories for a high level of definition in the representation of diet. This allows us to reflect both the physical background of UK diets as well as underlying production structures.

The aim of the analysis is to assess the maximum scale of mitigation achievable through transformative demand-side change in UK food consumption, without presupposing technological breakthroughs, in the context of achieving 1.5 °C consistent carbon budgets by mid-century.

The objectives of the research are as follows:

- To construct demand-side food emissions mitigation scenarios which reflect a transformative level of ambition with respect to recent net zero targets.
- To evaluate the potential of demand-side strategies to achieve mitigation across the UK food chain, under varying ambition levels.
- To assess the mitigation potential of combined pathways of varying levels of ambition.
- To develop a series of recommendations around what policy would be required to achieve the upper bound of mitigation potential as outlined in this analysis.

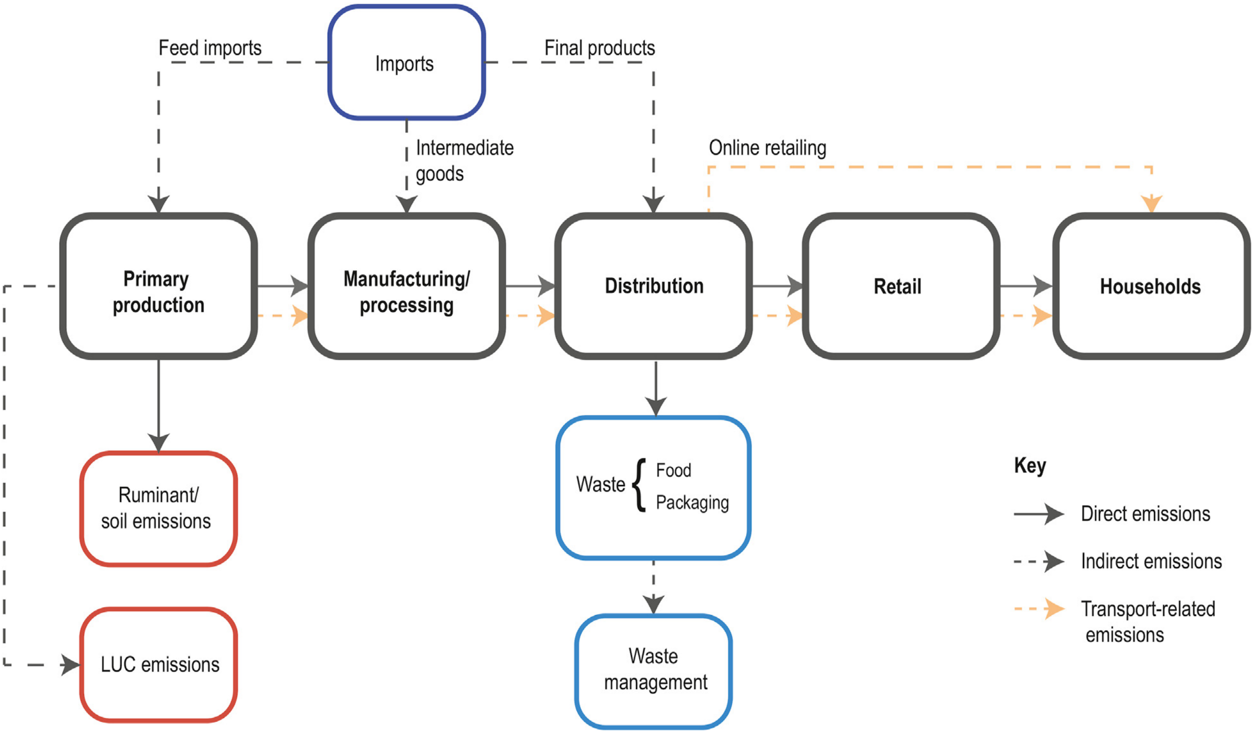

Fig. 1. Indicative emissions sources at different food system stages.

Section 2 reviews the literature on the UK food system and the scope of existing analyses; section 3 provides an overview of the modelling methodology (further information is available in the 'Supplementary Information', SI); section 4 discusses the results, limitations and future research directions of the work, whilst section 5 outlines our conclusions.

2. Evaluating options for more palatable food emissions

2.1. Existing scenario analyses

The majority of modelling studies of food system change operate on a global scale (Bajželj et al., 2014; Clark and Tilman, 2017; Grübler et al., 2018; Springmann et al., 2018) and typically model the effects of dietary change and food waste reduction (FWR), often with some limited representation of technological change. Many studies reach a consensus that dietary change has the most significant mitigation potential, but that a combination of all approaches will be necessary given growing global demand (WRI, 2019). There is also much variation in the degree of mitigation achieved by each measure (SI, Table S8); this may be a function at least in part of the chosen baselines and respective assumptions, for instance population, demography, and trends in these parameters. Ivanova et al. (2020) draw attention to the importance of system boundaries in their systematic review of mitigation potentials in the food sector.

Given recent commitments to limit global temperature rise to only 1.5 °C, analyses which provide scenarios of future nutrition under this constraint are highly valuable for policymaking. Two recent studies of this kind include Grübler et al. (p. 53, 2018a) and Willett et al. (2019). Although not the stated aim of the analysis, Grübler et al. (p. 53, 2018a) model 'production intensification and evolution of diets towards nutritious food with lower GHG emission footprints' as scenarios of global future dietary change. Potential weaknesses with their framing lie in their assumption of near constant levels of meat consumption (Grübler et al., 2018a), at least not allowing any rising consumption in the 'Global North'. These estimates appear conservative in light of recent trends towards plant-based diets. A research gap the present analysis attempts to correct is in updating analyses to reflect current attitudes towards reduced meat diets, particularly in developed regions.

Willett et al. (2019) present a notable study of the impact of wide-ranging dietary change, as a recent output from the EAT-Lancet Commission defining what would be a 'safe operating space for food systems' by constructing a 'universal healthy reference diet' (p. 447, Willett et al., 2019). Other pathway analyses at the global level include Springmann et al.'s (2018) analysis of food system change, and Bajželj et al.'s (2014) identification of demand-based interventions. Critical to constructing reference diet profiles is the consideration of both nutritional equivalence (Smetana et al., 2015) and the high 'inter-individual variability' in diet choice between for example self-described 'vegetarians' (p. 1, Rosi et al., 2017). This consideration is incorporated into the present modelling analysis. A subset of these scenario analyses present the opportunities for food system mitigation in the UK (Audsley et al., 2010; Blake, 2014).

There is also a substantial body of work using input-output analysis (IOA) to carry out food system emissions accounting (Camanzi et al., 2017; Kanemoto et al., 2019; Reutter et al., 2017; Reynolds et al., 2015; Salemdeeb et al., 2018). Broadly, Leontief input-output models are constructed from observed economic data and reveal interrelationships between industries that consume goods (inputs) from other industries making their own products (outputs) (Miller and Blair, 2009). The methodological approach of this analysis builds on the work of Behrens et al. (2017) in their use of an environmentally-extended MRIO database, EXIOBASE, coupled with detailed food modelling on a calorific basis in the context of recommended diets. Our approach differs however in the adoption of a single country case study of the UK, despite accounting for the trade impacts of diet. Owen et al. (2018) provide an assessment of the consumption-based energy, water and food footprints in the UK, using UKMRIO in addition to Structural Path Analysis (SPA) to determine the most effective intervention points for mitigation, emphasising the important of demand-side strategies. A wide range of IOAs of food emissions are available in the literature, however few are diachronic in addressing the effect of dietary change over time.

2.2. Demand-side mitigation options

2.2.1. Following government calorific guidance

Moderating calorific intake to the level of GDRs would have the benefit of addressing a growing global obesity crisis and the rapid spread of non-communicable disease (NCD) (Willett et al., 2019). In 2017, 65% of UK adults were considered to have an overweight or obese Body Mass Index (BMI), an increase of 13% in those with an 'obese' rating since 1993 (NHS Digital, 2018). The UK consumes an estimated 15% more calories than is nutritionally recommended (p. 5, Blake, 2014). Overconsumption has been compared to a form of food waste in supplying calories beyond nutritional requirements (p. 81, IPCC, 2018). Conversely, addressing food waste may be a result of overconsumption in the first instance, that is, buying more than is required.

There is therefore a clear public health rationale for moderating overconsumption in the UK. McMichael et al. (p. 1253, 2007) indicate the need for an international 'contraction and convergence strategy'. Grübler et al. (p. 53, 2018) assume that there are 'moderate increases in daily calorific intake' to a maximum of 3500 kcal in the 'Global North'. A report by WRI (2019) found that reducing calorific intake in high consumer categories, assuming a 50% reduction in those considered overweight or obese, would result in only a 2% reduction in global calorie intake, but with greater implications for the availability of land. In their UK-centred analysis however, Blake (p. 5, 2014) found that by moderating calorific intake to nutritionally recommended levels, emissions were reduced by 19%. There is evidently space to address two concurrent public health crises in obesity and climate change.

2.2.2. Dietary transitions

Many studies focus exclusively on the role of changing diet in mitigating food-related emissions. As Table 1 highlights, dietary transitions were the most common mitigation option in the selected modelling analyses.

Dietary transitions are a key focus given the disproportionate emissions intensity of animal-based products. Per unit of expenditure (GBP £), meat products consumed in the UK are 21 times more emissions intensive (CO_2e) than the average for fruit, vegetables and cereals, and dairy is 3 times more emissions intensive. Green Alliance estimated that livestock agriculture is responsible for around 70% of emissions from the agricultural sector in the UK (p. 10, Green Alliance, 2019), and the CCC estimated that 58% of UK agricultural emissions were attributable to cattle and sheep farming in 2016 (p. 31, CCC, 2018). This has critical LUC impacts and opportunity costs for carbon sequestration, as well as significant direct emissions via ruminant enteric fermentation. Across all environmental indicators examined by Clark and Tilman (p. 8, 2017), they found that ruminant meat had 20-100 times more impact than plant-based foods, and that dairy, 'pork, poultry, and seafood had impacts 2–25 times higher than plants per kilocalorie of food produced.'

However, it may be simplistic to create artificial divisions between animal and plant-based diets as an indication of environmental impact. As González et al. (2011) note, use of airfreight and heated greenhouses can overrule this binary characterisation, with some vegetable proteins having greater environmental impact due to their import origins and the mode of production used. This is a strength of the use of LCAs in determining the composition of optimally low emissions diets, and a reason for the extensive work on the LCA of food (Garnett, 2014; Sanjuán et al., 2014; Smetana et al., 2015; Virtanen et al., 2011). However, in a recent study by Nemecek and Poore building a 'multi-indicator global database' of dietary environmental impacts, they find that 'the impacts of the lowest-impact animal products exceed average impacts of substitute vegetable proteins across GHG emissions' and other environmental impacts (p. 4, 2018).

2.2.3. Food waste reduction

Food waste is a frequently modelled mitigation option and subject of food policy given it is relatively uncontroversial. In the UK, households are responsible for around 70% of all food waste (p. 34, CCC, 2018), of which 60% is avoidable (p. 14, Green Alliance, 2018). Action at the consumer end regarding food waste is disproportionately effective given the accumulation of 'embedded emissions' throughout the food supply chain (Bajželj et al., 2014). By preventing waste at the household level, there is upstream impact in reducing overall demand for food production. Similarly, Garnett (p. 11, 2014) argues that food waste is in fact a source of 'financial inefficiency', and therefore waste reduction helps promote food security, reduce embedded emissions, and capture cost savings creating a 'triple win'. Scott et al. (2018; Green Alliance,

Table 1
Overview of mitigation options considered in studies modelling food system emissions scenarios. An X indicates this is included, (?) that this is unclear, and (-) that it is excluded. This is non-exhaustive.

Source	Mitigation option addressed				
	Dietary transitions	Calorific intake moderation[a]	Food waste reduction	Technological improvement	
				Agricultural	Industrial
Audsley et al. (2010)	X	-	X	X	X
Bajželj et al. (2014)	X	-	X	?	-
Blake (2014)	X	X	X	-	-
Bryngelsson et al. (2016)	X	-	X	X	-
Clark and Tilman (2017)	X	-	-	X	-
Garnett (2014)	X	-	X	X	?
Grübler et al.(2018)	X	-	-	X	?
Springmann et al. (2018)	X	-	X	X	X
Stehfest et al. (2009)	X	-	-	-	-
Willett et al. (2019)	X	X	X	X	-
WRI (2019)	X	X	X	X	?

[a] Although some studies model calorific change, they do not examine scenarios to actively moderate calorific intake to healthy levels, as is the case in Grübler et al. (2018a) for example.

2018) indicate that food and drink based resource efficiency would contribute to reducing 16% and 12% of the emissions ‘overshoot’ predicted for both the fourth and fifth carbon budgets.

Springmann et al. (2018) note that cereals, vegetables and fruit suffer disproportionately greater waste rates than meat. This indicates that within the suite of food system mitigation options food waste could make a less significant contribution since waste rates are higher for the least GHG-intensive food groups. It also points to the need for targeted food policy which works to prioritise waste reduction for the most GHG-intensive products. Packaging also contributes to the waste emissions of food with particular issues presented by the drinks industry (Defra, 2011). A compromise between sufficient packaging to preserve goods and thus avoid waste, whilst reducing the embodied emissions of the packaging is required. There is scope to take advantage of current attitudes towards plastic packaging to leverage change in this area. In all, packaging constitutes only 7% of food’s impact, therefore it is not considered a critical gap in this study (Garnett, 2011).

3. Data and methods

We constructed a hybrid physical input-output food system model to implement the three mitigation scenarios according to varying levels of ambition (Fig. 2).

The ‘current’ case is a control variable, indicating only the demand change anticipated with a population and demographic developments. The BAU case assumes extrapolation of recent trends to 2050 (for example assuming continued adoption of plant-based diets). Extrapolation assumes a rate of change in-keeping with historical trends; the rate will vary according to each scenario and the available data on past trends for each mitigation option (see SI, sections 1.1.2., and 1.2.4.). The BAU continuation of trends would in itself cause substantial shifts in diet from the current situation (see Table 3).

The high ambition case represents an upper bound of policy effort towards mitigating food emissions through demand-side action. Evidence on the precedent of policy achieving the necessary scale of dietary change is lacking, therefore in each case, a paradigm shift in the structure and degree of policy on UK diet is imagined to support the necessary changes. The low ambition scenario indicates an intermediary level of effort, with less stringent policy assumptions. All scenarios use a 2017 year baseline, with the assumption that mitigation ‘starts’ in 2020.

The following describes the mathematical construction of the scenarios and their respective assumptions. Full documentation of the underlying assumptions in each ambition case is found in the SI.

3.1. Designing demand-side mitigation options

The assumptions of the mitigation options per ambition level are outlined in Table 2.

3.1.1. Following government calorific guidance

The calorific intake scenarios assumed the need for transitions to promote optimal public health and we consider what the associated emissions reduction would be with a reduction in overweight and obesity levels to 2050. Baseline calorific intake was calculated using official statistics, namely the Family Food Survey (Defra, 2018). A correction for underreporting was incorporated (Harper and Hallsworth, 2016), resulting in an assumed average UK calorific intake of 2871 kcal per day per capita excluding additional calories from food bought but not eaten.

To project BAU calorie change, historic trends were extrapolated using FAOSTAT data (FAO, 2020). This increased per capita calorific intake to 3154 kcal in 2050. The high ambition case assumes that average adult intake is 2500 kcal (per capita, per day) in 2050 in line with the GDR for adult men; for women recommended consumption is 2000 kcal (PHE, 2016). A gender weighted average consumption for the UK adult population would be 2250. Our assumption of 2500 kcal allows a buffer of additional calories beyond the minimum, accounting for different levels of physical activity and metabolic rates.

Willett et al. (p. 454, 2019) adopt an assumption of 2500 kcal in their ‘planetary boundaries’ diet, citing that whilst other analyses use an assumption of 2100 kcal this presupposes a lower initial Body Mass Index (BMI) and ‘would leave little room for public health goals to increase physical activity because this will require additional food energy’. There is indeed some debate in the literature over the proportion of daily energy intake required to balance physical activity-induced energy expenditure (AEE), and the intake required for maintaining a healthy weight will be dependent on an individual’s physical activity levels and body mass (Westerterp, 2013). A number of studies assess the increase in energy expenditure resulting from a programme of increased physical activity; one such study found an increase of 16% in energy expenditure (Fontana et al., 2007), another finding a 20% increase (Bingham et al., 1989). The requirement is often considered somewhere between 10 and 30% of total energy expenditure (Westerterp, 2013). Therefore, our provision of a 10% buffer in our high ambition case, alongside the precedent for this assumption in Willett et al. (2019), makes the

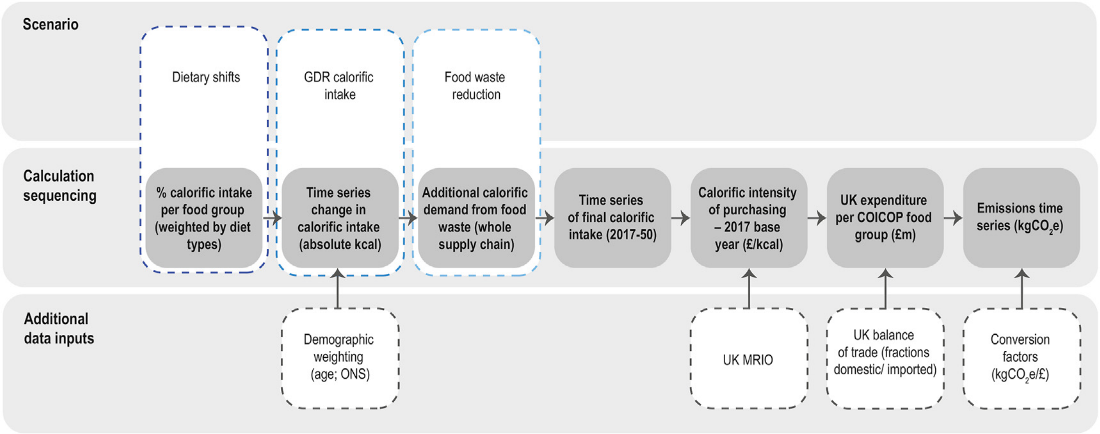

Fig. 2. Schematic of food system model and calculation sequencing.

Table 2
Overview of mitigation option assumptions by ambition level.

Mitigation option	Functional unit	Value in 2050			
		Current	BAU	Low ambition	High ambition
Recommended calorific intake	Kcal/pc/day (for the average UK adult)	2871	3154	2686	2500
Dietary transitions	% omnivores in UK population	66.5	29	17	5
	% healthy diet in UK population	21	25	27	28
	% vegetarian in UK population	9.5	31	36	42
	% plant-based in UK population	3	15	20	25
FWR	% reduction pa in 2020–25	–	2.25	2.5	3.33
	% reduction pa in 2026–30	–	2.25	2.5	3.33
	% reduction pa in 2031–35	–	2	2.5	3.33
	% reduction pa in 2036–40	–	2	2.5	3.33
	% reduction pa in 2041–45	–	2	2.5	3.33
	% reduction pa in 2046–50	–	2	2.5	3.33
	Cumulative reduction against 2020 levels (%)	–	62.5	75.0	99.9

Table 3
Summary of territorial emissions for the combined scenarios.

Metric	Ambition case			
	Current	BAU	Low ambition	High ambition
2050 emissions (MtCO$_2$e)	44	32	24	19
Cumulative emissions (2017–2050) MtCO$_2$e	1431	1252	1124	1037
Percentage change in cumulative emissions against baseline (%)	–	−13	−22	−28
Annual change in emissions (2050) (%)	+11	−18	−39	−52

assumption defensible.

It remains a substantial reduction from current consumption levels and also counteracts the assumption that the UK population currently and uniformly meets a basic level of dietary needs, which evidence on the rise in rates of food poverty contradicts (The Trussell Trust, 2019). Therefore, 2500 kcal as an upper bound of ambition is considered feasible in the specific context of the UK. The low ambition case of achieving 2686 kcal per capita per day in 2050 assumes 50% progress towards closing the gap between current levels of calorific intake and the high ambition case, suggesting an intermediary level of policy effort.

Recommended calorific intake is dependent on demographic factors such as age. We weighted the calorie scenarios by age groups according to the GDRs and Office for National Statistics population projections, taking an average value between genders (PHE, 2016; ONS, 2019). It is assumed that moderation of calorific intake to healthy levels only occurs in individuals between 15 and 64 to which the 2000 (female) and 2500 kcal (male) GDR applies (PHE, 2016). The calorific intake of age groups 0–1, 2–3, 4–6, 7–10, 11–14, and 65+ are fixed according at the level of the GDRs. Although there is evidence to suggest that moderating calorific intake in older populations contributes to better health outcomes (Han et al., 2011), such considerations are beyond the scope of this analysis. Calorific intake per capita in each age group ($\mathbf{C_a}$) was calculated (in kilocalories), according to the relative difference between the GDR for each age group ($\mathbf{C_{GDR\ a}}$) and the GDR *adult* intake ($\mathbf{C_{GDR\ adult}}$). Equation (1) applies this to average calorific intake ($\mathbf{C_{avg}}$) to scale consumption to each age group.

Annual average calorific intake ($\mathbf{C_{avg}}$) is calculated logistically from the estimate of current calorific consumption in the Family Food Survey (Defra, 2018), accounting for underreporting, as well as the assumptions of change over time. S-shaped trends implemented by a logistic growth function are commonly used to model and forecast a number of nonlinear socio-technical and demographic changes (Meyer, 1994). In this case logistic interpolation was assumed to be appropriate, as dietary change will involve the population-wide diffusion of new social norms (Miller and Prentice, 2016).

The GDR values for $\mathbf{C_{GDR\ a}}$ and $\mathbf{C_{GDR\ adult}}$ are fixed across the time series. Adult age groups are derived from the GDRs (PHE, 2016) and include: 15–64, 65–74, and 75+.

$$C_a = C_{avg} \cdot \left(1 + \frac{C_{GDR\ a} - C_{GDR\ adult}}{C_{GDR\ adult}}\right) \tag{1}$$

3.1.2. *Dietary transitions*

To calculate baseline dietary intake, the composition of an average national diet in percentage calorie intake per food group was determined (by COICOP categories), drawing on data from the National Diet and Nutrition Survey (NDNS) (PHE, 2019). We considered 4 diet types profiled in the literature and their composition by food group, namely: omnivorous, healthy, vegetarian, and plant-based. The ‘healthy’ diet appears frequently in the literature and generally involves lower red meat consumption under both public health and climate change rationales.

The inclusion of an average ‘healthy’ diet rather than prescriptive pescatarian or poultry-only diets allows greater flexibility for individual choice in the construction of personal diet. Seventeen diets across six key studies were used (see SI, Table S1), and percentage composition in calories (kcal) was calculated. The use of percentage composition allowed diets to be isocaloric, often a limitation of diet modelling studies where total plant-based calorific intake is commonly lower than for omnivorous diets. A barrier to analysis of diet scenarios in the literature is the inconsistent use of classification systems; bridging these various systems to COICOP allowed dietary assumptions from multiple studies to be accessed and analysed in a harmonised format. However, aggregation to the 69 COICOP groups could have resulted in some loss of definition in diet profiling, given the lack of representation for alternative proteins (e.g. Quorn) in the system. Where alternative proteins were documented in the studies they were incorporated to COICOP vegetable categories.

To assess calorific intake on a product basis, annual calorific intake at the population scale ($\mathbf{C_{pop}}$) was first calculated using equation (2), where the total population data ($\mathbf{P}$) derived from ONS (2019) is multiplied by the sum for each age group of the proportion of the population of each age category ($\boldsymbol{\rho_a}$) multiplied by the calories consumed per capita in this age group ($\mathbf{C_a}$) as in equation (1).

$$C_{pop} = P \sum_a \rho_a \cdot C_a \tag{2}$$

For each food group ($\mathbf{f}$), equation (3) is used to calculate the total calories of this food group consumed in a given year across the population ($\mathbf{C_f}$). The total calories consumed in the year ($\mathbf{C_{pop}}$) is multiplied by the sum for each diet of the proportion of the population following the diet ($\boldsymbol{\rho_d}$) multiplied by the proportion of calories in this diet that are supplied by the given food group ($\mathbf{f_{fd}}$).

$$C_f = C_{pop} \sum_d \rho_d \cdot f_{fd} \tag{3}$$

An ‘average’ of literature-based dietary compositions was calculated for each of the four headline diet types since the profiles of indicative diet types are highly variable between analyses. Fig. 3 outlines the final composition of the four diet types. Assumptions of the relative shares of each diet type in the population were then made and a weighted average national diet constructed (see Table 3).

In the BAU case the recent trend in uptake of plant-based, vegetarian and reduced meat diets is predicted to continue. Empirical data on current dietary composition in the UK is limited, and often only available as ad-hoc surveys (Waitrose and Partners, 2019; YouGov, 2017). Similarly, many studies and national datasets are subject to both mis- and under-reporting. For example, purportedly vegetarian participants have reported consumption of red meat (Bradbury et al., 2017), and one ‘vegetarian’ scenario in Bryngelsson et al. (2016) includes consumption of beef from dairy cattle. National dietary data collection efforts are known to under-report, for instance the NDNS (Harper and Hallsworth, 2016; PHE, 2019). There are no clear datasets which fully reflect the widely reported changes in consumption patterns in the UK, for example relating to the ‘year of the vegan’ (assumed to be in 2019) (Hancox, 2018; Jones, 2018). A combination of sources was used to infer trends of plant-based diet uptake at the national scale (Ipsos MORI, 2016; Waitrose and Partners, 2019).

Given the lack of baseline data on diets, in projecting change forwards, the scenarios are based on qualitative assumptions of a general direction of travel input logistically to the model. Theoretically a substantial majority of the population could follow a plant-based diet (accounting for different health-related and cultural dietary needs). There is little evidence on what could be considered a reasonable ‘upper bound’ for ambition in terms of dietary change, just as there is little evidence on existing shares of diet types in the population. Many studies consider a percentage reduction in the consumption of red meat for instance, whilst we use diet types across the population to reflect that dietary transitions affect all food groups in the compensatory consumption of other products.

To capture the relative transitions between diet types, a number of assumptions were made. The limited data on historical trends informed the level of change in the BAU scenario. In the BAU case there is a 34% reduction in the percentage of the population following any kind of omnivorous diet, and a transition to approximately half of this omnivorous demand being met by a ‘healthy’ variant. There is a corresponding increase of 34% in the proportion following a vegetarian or plant-based diet, of which an increasing fraction is allocated to a plant-based consumption. In the high ambition case, there is an extension of ambition beyond the modelled BAU rate of change (which is of itself ambitious) resulting in a 54% reduction to omnivorous consumption against current levels, of which the majority is now satisfied by the ‘healthy’ variant. There is a corresponding increase of 54% in the proportion of vegetarian or plant-based consumption, of which a greater proportion is from plant-based diets. The low ambition case assumes an intermediary level of policy effort between the BAU and

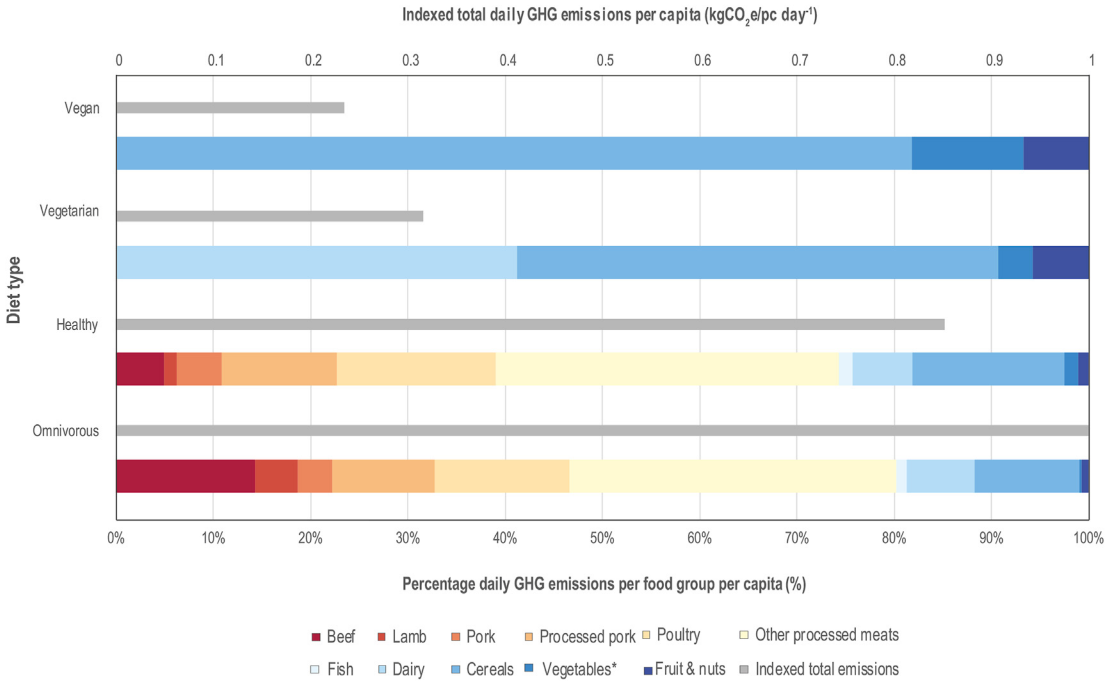

Fig. 3. Distribution of consumption-based emissions by headline food group for reference diet types, and indexed total daily GHG emissions per capita per diet. This assumes isocaloric intake of 2500 kcal for comparison purposes. ‘Indexed total daily GHG emissions per capita per diet’ refers to the emissions attributable to one adult’s daily consumption, according to which of the four reference diet types listed the individual follows.

high ambition scenarios, given the existing level of ambition in the BAU case.

The degree of dietary transition in the high ambition case is considered the upper bound of policy ambition in light of the challenges involved in incentivising dietary change and the lack of evidence in policy achieving this to date. Additionally, giving scope for at least a third of the population to continue following an omnivorous diet is both realistic and sensitive to cultural factors at play in the composition of diet.

3.1.3. Food waste reduction

Reducing food waste and losses is a key public policy target, as cited in the recent Resources and Waste Strategy (HM Government, 2018). It is also a means of avoiding additional food demand, by making more efficient use of the food that is currently delivered through the UK food system.

To calculate total calorific demand incorporating additional demand for calories from food waste per food group, equation (4) was used. Total demand for calories per food group per annum at the population scale ($\mathbf{D_f}$) was calculated by multiplying the total calories of a food group consumed in a given year across the population ($\mathbf{C_f}$) by the rate of food waste per food group ($\mathbf{W_f}$).

$$D_f = \left(C_f \cdot \left(1 + W_f\right)\right) \tag{4}$$

In-keeping with the demand-side focus of the analysis, we only considered the potential for FWR at the consumer end of the supply chain, namely the household and retail stages, and how this varies between food categories. Available data on food waste is of relatively poor quality, consistency, and rarely up-to-date. We aligned estimates of supply chain food waste (Caldeira et al., 2019) and estimates of avoidable waste per food group (Bryngelsson et al., 2016) to the COICOP classification. Waste of liquids was not included since there is arguably no avoidable fraction of liquid waste. This could constitute a further model refinement.

In the BAU case, trends in FWR were extrapolated to 2050, resulting in per annum reductions of 2.25%. In the low ambition case, Sustainable Development Goal 12.3 is assumed to be met, halving food waste by 2030 (against 2015 levels) (United Nations, 2019), and a comparably ambitious target set from 2030 to 2050. In the high ambition case, all avoidable food waste is eliminated in the UK. The percentage reductions were assumed to be linear. The waste rate time series were then input to the calorific demand profiles as a multiplier, indicating the quantity of additional calories required by UK consumers due to food waste. The upper ambition levels assigned to waste represent the theoretical maximum reductions to waste that could be achieved in a case of significant policy support.

3.2. Constructing a demand-side food system model

To combine the scenarios, the time series of calorific intake change (based on the assumptions outlined above) were linked to population estimates (weighted by age and total population projections). The population-based calorific intake time series were then applied to the diet scenarios, by multiplying the percentage of calories for each food group in the average UK diet against the absolute population-weighted calorie time series (Fig. 4). The time series of additional calorific demand from food waste were then used as a multiplier against the diet and population-weighted calorie values.

To calculate the results on a territorial basis (accounting only for emissions associated with UK production for UK demand), the fraction of UK expenditure in 2017 on food produced in the UK was calculated. The 2017 UK expenditure by COICOP group was divided by the total UK per annum calories to produce a calorie intensity of spend (£/kcal). This constant intensity value was multiplied by the various calorie time series to produce time series of UK expenditure on food products of UK origin. A conversion factor of calorific intensity of spend ($\mathbf{M_f}$; £/kcal) was created to mediate between the economic IO data and values for final calorific demand. This was achieved by dividing total annual expenditure per food group in 2017 ($\mathbf{X_f}$; £m) by $\mathbf{D_f}$ (equation (4)).

The IO data was derived from the UKMRIO database constructed by the University of Leeds to calculate the UK's consumption-based account (CBA) (UK Government, 2019). MRIO databases have been adopted by environmental economists due to their ability to make the link between the environmental impacts associated with production techniques and the consumers of products. A UK GHG footprint model needs to be able to measure the impact of UK consumption of products, considering both domestic and foreign production supply chains. This means the MRIO table needs to have information about flows of products from abroad, to both UK intermediate demand and final demand. Production efficiencies vary between different producers, meaning that the impact per pound spent may be larger for a product from country A than from country B. The UKMRIO model represents the flow of trade between 15 world regions.

The expenditure time series was converted to GHG emissions (kgCO_2e) using emissions intensity of spend (kgCO_2e/£ intensity) data as derived from the MRIO framework. Data from the 2016 Annual Living Costs and Food Survey (LCFS) underpins the MRIO database (UK Data Service, 2019), showing weekly expenditure by the 5041 households involved in the survey. This data is used to portion total UK household expenditure to top level COICOP categories from the MRIO database.

'Independent variable' scenarios were also created in which only one mitigation option changes at a time (e.g. diet, calories, waste), to gauge the effect of individual options. The results were also calculated on a consumption basis by multiplying the fraction of UK expenditure on imported produce by the respective conversion factors for each country of origin. This reflects the emissions associated with UK demand incorporating embodied emissions in imports.

To calculate territorial emissions, equation (5) was used, where emissions ($\mathbf{E_T}$) are the sum for each food group ($\mathbf{f}$) of the total calorific demand (including waste, $\mathbf{D_f}$), and converted to expenditure ($\mathbf{M_f}$). This is then multiplied by the proportion of expenditure met by domestic production ($\mathbf{d_f}$) and the carbon intensity of domestic production ($\mathbf{G_{d\ f}}$). This comprises territorial emissions associated with domestic consumption, and not UK production towards overseas consumption (i.e. for export). Expenditure is calculated for each year based on the $\mathbf{M_f}$ factor and calorie time series.

$$E_T = \sum_f D_f \cdot M_f \cdot d_f \cdot G_{d\,f} \tag{5}$$

Consumption-based emissions were similarly calculated, but used the country specific conversion factors based on the fraction of spend on each nation's goods from the MRIO framework. Following equation (6), consumption emissions ($\mathbf{E_C}$) are the sum for each food group ($\mathbf{f}$) of the calorific demand ($\mathbf{D_f}$) converted to expenditure terms ($\mathbf{M_f}$), multiplied by the sum for each region ($\mathbf{r}$) of the proportion of expenditure on this food group within the region ($\mathbf{X_{fr}/X_f}$) multiplied by the carbon intensity of production for the food group within that region ($\mathbf{G_{fr}}$). Territorial emissions are a special case of this, where only a single production region (the UK) is of interest.

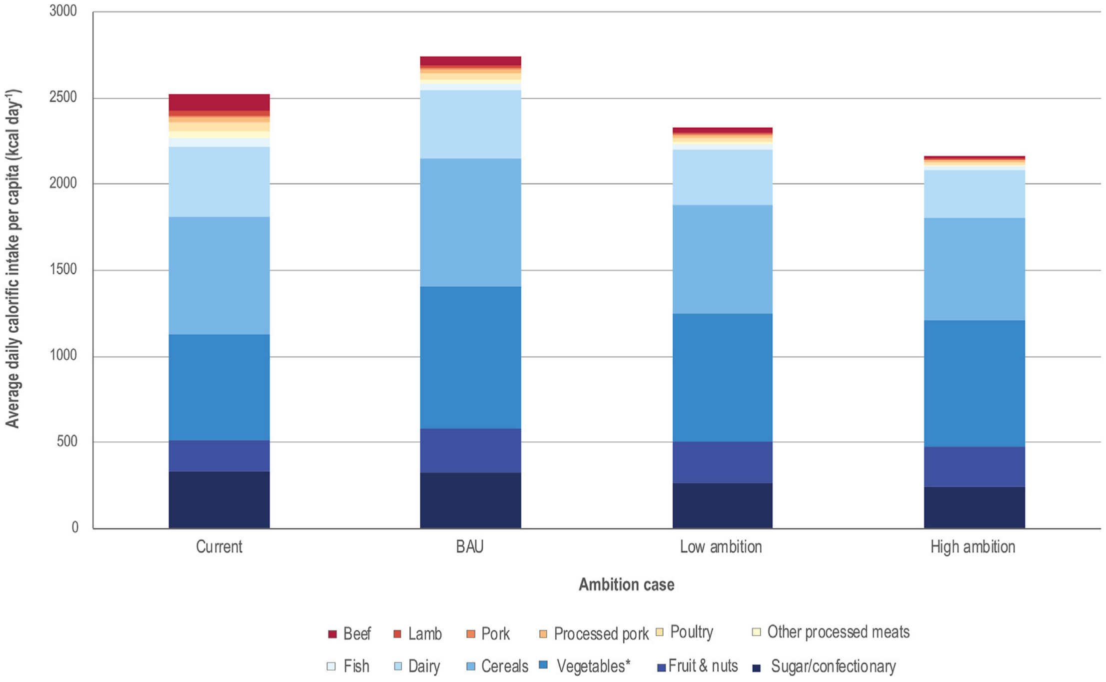

Fig. 4. Composition of diets by daily calorific intake and headline food groups in each of the ambition cases.

$$E_C = \sum_f \left(D_f \cdot M_f \cdot \left(\sum_r \frac{X_{fr}}{X_f} \cdot G_{fr} \right) \right) \tag{6}$$

3.3. Boundaries of the analysis

To ensure a consistent approach certain elements of the food system were considered out of scope. Reliable UK specific data on LUC emissions that could readily be integrated to the model was lacking, so this was not considered to avoid using over-simplifying assumptions. Gains in production efficiencies for the agricultural and food and drink sectors were also considered out of scope, due to data limitations associated with the heterogeneity of the sectors. Therefore, our emissions scenarios are likely an overestimate of future emissions given the probable improvements in production intensities. Emissions from the production of ruminant meat, which constitute a large share in the impact of current diets, are particularly hard to mitigate through technology however, therefore demand moderation would prove an effective mitigation option in this area.

We assume that the UK balance of trade in 2017 holds constant to 2050 for each food group, which is unlikely. However, it is equally difficult to predict possible trajectories of change in trade given current geopolitical tensions, the impacts of climate change, and economic uncertainty. When considering diets, we assume this includes all food consumed irrespective of the location of consumption (e.g. takeaways, restaurants). Changes to food preparation techniques (e.g. cooking methods) could also have important additional implications for the secondary use of energy and could valuably be explored further.

4. Results and discussion

4.1. The current UK food footprint

Fig. 5 indicates the emissions flows at baseline (2017) levels of demand on a consumption emissions basis. The results indicate the emissions associated with UK production for UK demand (i.e. not for export). The food groups are ‘headline’ groups aggregated from the 69 COICOP categories used in the analysis (for breakdown, see SI, Table 4.1). Meat categories are disaggregated given their greater relative contribution to total emissions.

The figure highlights the contribution of meat products (particularly processed meats) to UK production emissions, and the large fraction of emissions attributable to wasted food.

4.2. Future territorial food emissions

The future scenario results indicate that without mitigation UK food emissions (UK demand for UK produce) would likely increase to 2050, as a function of population growth and current consumption levels, despite the simultaneous transition to an ageing population. However, the results also suggest that there is scope to reduce our annual emissions in 2050 by over half if the mitigation options outlined in this analysis are pursued. The mitigation pathways could reduce territorial UK food emissions by as much as 52% against current levels, marking a 28% reduction in cumulative emissions against the baseline from 2017 to 2050 (Table 3). Results are presented in total emissions (not per capita) since this is what ultimately determines the achievement of the UK’s carbon budgets.

Fig. 6 shows that in the BAU case, the emissions from UK food demand are set to reduce, assuming the continuation of recent trends in voluntary diet change. It should be noted that in itself, the BAU case is highly ambitious in assuming the degree of change suggested over recent years. In comparison to the results for individual mitigation options (where all other variables were held constant at current levels), the combined results show the benefit of a ‘hybrid’ mitigation approach, employing multiple options, and

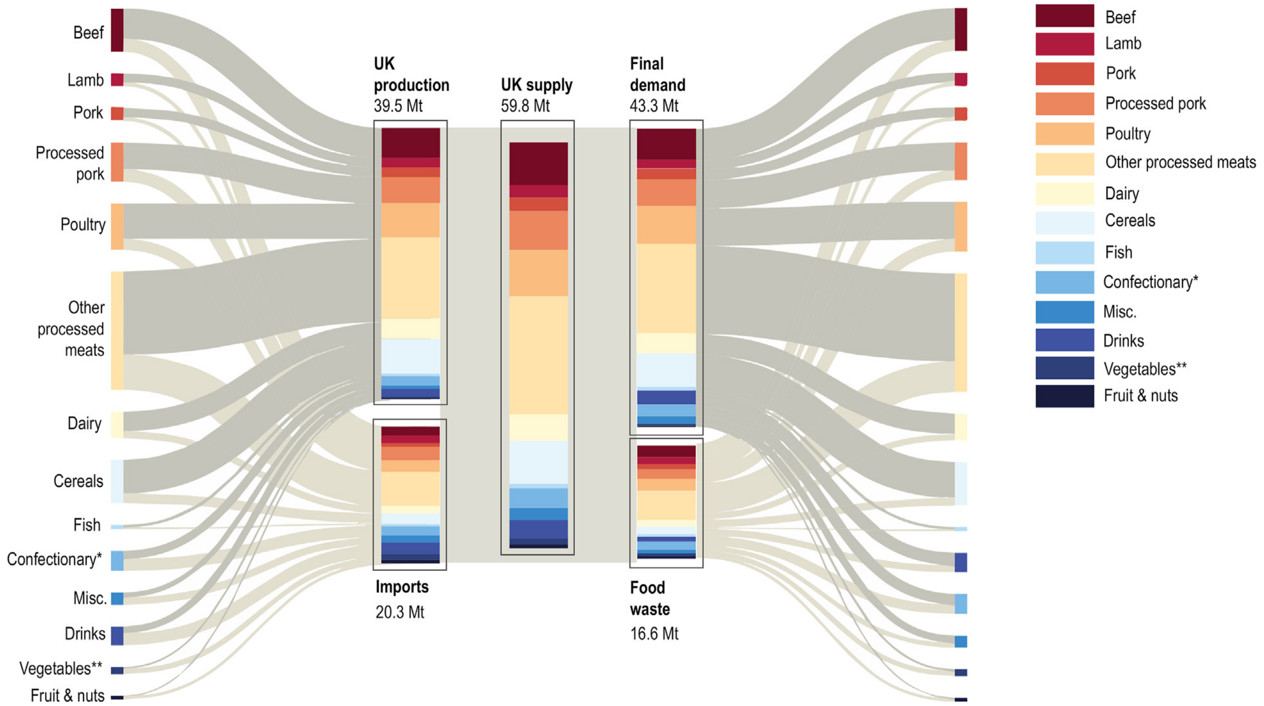

Fig. 5. Sankey diagram indicating consumption-based emissions flows per headline food category in megatonnes CO_2 equivalent ($MtCO_2e$), the proportion of emissions from food waste and delivery to final demand, based on current consumption (2017 levels). Totals may not sum due to rounding. Data is from final analysis not MRIO data. *Confectionary also includes sugar products (e.g. conserves). **Vegetables includes vegetable fats and alternative proteins.

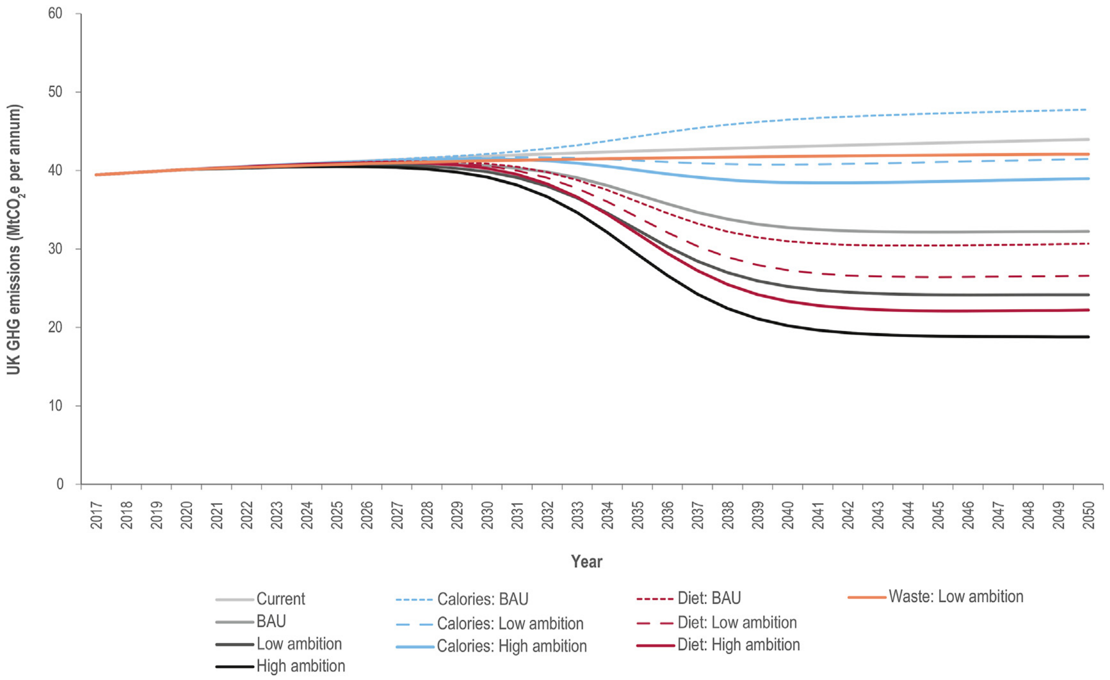

Fig. 6. Territorial emissions time series for the ambition scenarios and individual mitigation options. The ambition scenarios are in greyscale, whilst individual mitigation options are in red (dietary transitions), and blue (calorific intake). The independent food waste scenarios did not produce time series of a significant difference, therefore only the high ambition case is shown (orange solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

achieving an additive emissions reduction effect.

4.3. Future UK food footprints

The consumption-based results reveal the significantly higher footprint of UK consumption when incorporating emissions embodied in imported produce (Figs. 7 and 8). The footprint of current UK food consumption is 52% greater when considered on a consumption-basis.

The relative difference between the territorial and

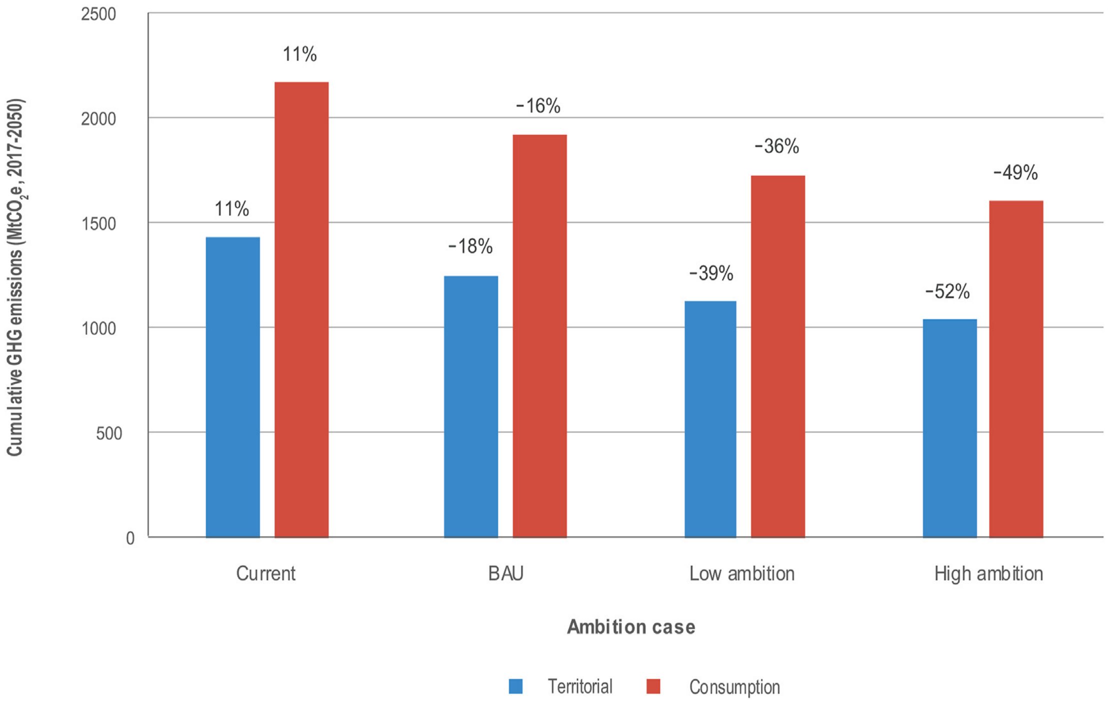

Fig. 7. Cumulative GHG emissions (2017–2050; territorial and consumption) according to each ambition case. Absolute percentage change (from 2017 levels) are indicated by the data labels. 'Current' indicates changes in emissions resulting from population growth.

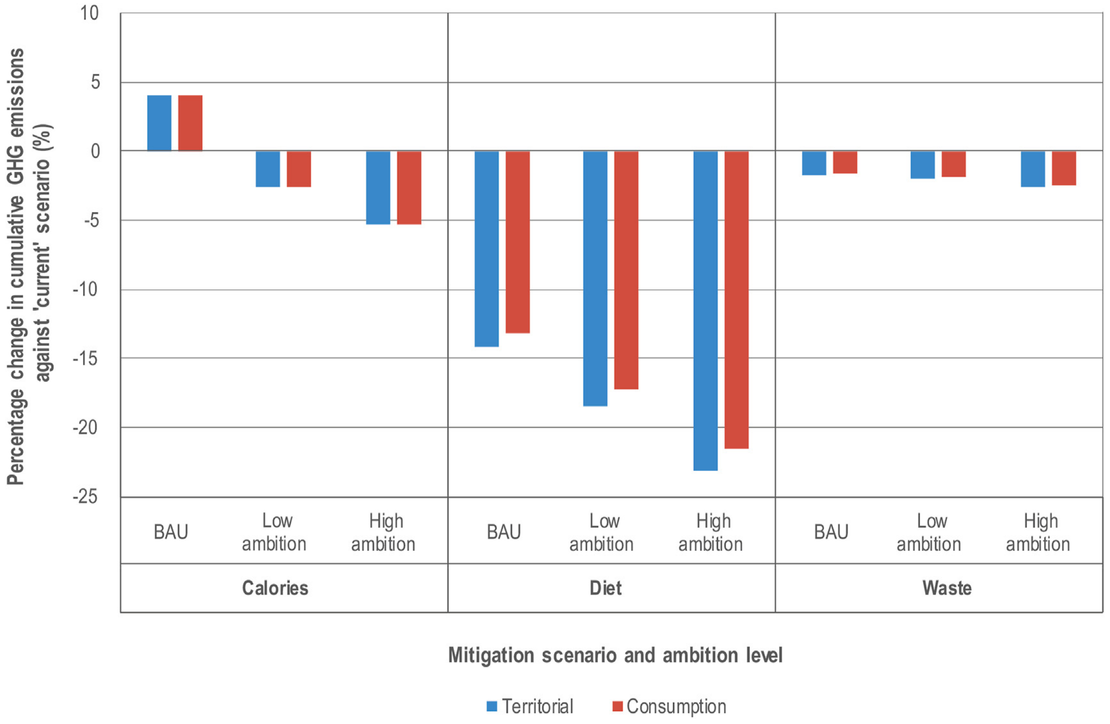

Fig. 8. Cumulative GHG emissions (2017–2050; territorial and consumption) according to each mitigation option and ambition case.

consumption-based footprint in 2050 varies according to each scenario (Table 4). In the dietary transitions scenario the footprint increases 10% relative to current consumption-based emissions in 2050. In the high ambition scenario (all options) consumption-based emissions are 11% greater than those for the current pathway in 2050. The difference in both cases may be attributable to changing product shares in final consumption, that is, whilst the origins of imports remain constant, modal shifts in the volume of each product result in changing volumes of imports by region.

Through comparison of Figs. 7 and 8, it is clear that the relative scale of reduction achieved between territorial and consumption-based accounting approaches is not significantly different,

Table 4
Overview of relative differences between territorial and consumption-based footprint in 2050 according to ambition levels and scenario options.

	Percentage difference between territorial and consumption-based emissions in 2050 (%)			
	Ambition level			
	Current	BAU	Low ambition	High ambition
All options	+52	+56	+59	+62
Government calorific guidance	–	+51	+52	+52
Dietary transitions	–	+56	+58	+62
FWR	–	+52	+52	+52

excepting the diet scenario. This perhaps indicates the role of modal shifts in the structure rather than the quantity of demand.

The comparative results also indicate the greater scale of mitigation required when working on a consumption basis. Demand-side interventions have an important effect on consumption-based emissions as they impact both domestic production and the demand for imports. This approach also allows developed nations to take greater responsibility for the emissions associated with their consumption patterns.

4.4. Demand-side mitigation and policy towards net zero

The results by mitigation option (as in Fig. 8) indicate that some strategies contribute significantly more to overall mitigation in the food system. For example, the dietary transitions option results in a reduction to annual GHG emissions of 22% (BAU), 33% (low ambition), and 44% (high ambition), despite population change. In contrast the mitigation from FWR is not sufficient to offset increased demand from population growth. The BAU case for calorie change would result in a 21% increase in annual emissions, 10% more than the effects of population growth alone. Whilst we found that annual territorial GHG emissions could be reduced from current levels by as much as 52% by 2050, the mitigation potentials outlined clearly cannot be realised without effective policy action at pace.

Recent government commitments to achieving a sustainable food system include the National Food Strategy and Defra's Farm Emissions Reduction Plan (both due for publication in 2020) (CCC, 2019), and the Industrial Strategy Challenge Fund on 'Transforming Food Production' (Innovate UK and UKRI, 2019). Beyond a public health and nutrition basis, there can be seen to have been limited policy intervention in national diets to date (Röös et al., 2017). The scope of mitigation achievable on territorial and consumption-based emissions through demand-side action, coupled with the known and available nature of this type of change make a cogent argument for enacting these mitigation options in policy. The following explores the relative contribution of each option and potential policy mechanisms for their implementation.

4.4.1. Following government calorific guidance

The results indicated moderately large mitigation potential in GDR aligned calorific intake, but the spill-over benefits to public health are arguably even more significant. The results indicated that maximum reductions of 5% in cumulative GHG emissions (2017–2050) and a 1% reduction in emissions intensity per capita are possible.

If the UK follows a BAU trajectory there are likely to be emissions gains (of approximately 4% cumulative emissions to 2050), resulting from both population growth and higher mean calorific intakes. It would therefore be advisable for policy to at least aim to offset this growth for environmental and health reasons. This is particularly necessary given the global 'contraction and convergence' approach required for calorie consumption (McMichael et al., 2007), where developing countries need to substantially increase their daily calorie intake per capita to meet basic human needs, as indicated by the SDGs (UN, 2019). Moderating calorific intake in developed nations with greater relative availability and choice of food products is therefore a question of common but differentiated responsibility.

However, although there is a public health rationale to reducing calorie overconsumption, the question of what policy mechanisms could encourage this is highly contentious. Calorie overconsumption is not a blanket issue across UK households and is the product of various social drivers. Although we have indicated the potential for demand-side change there is need to avoid damaging narratives around consumption which place responsibility solely with the consumer. In reality, structural problems such as access to food and broader issues of inequality are critical and lie beyond the scope of consumers to address.

There are critical distributional dimensions to the food system debate in the UK. Although rates of obesity appear to be high, there is a simultaneous crisis with food poverty and increasing dependence on food banks. The Trussell Trust, a large UK food bank network, reported a 19% increase in supplies distributed between 2018 and 2019, with a 73% increase in food bank use over the previous 5 years (The Trussell Trust, 2019). Obesity and food poverty are closely linked; with rising food costs households may be forced to purchase cheaper but unhealthier foods. Policy to encourage sustainable consumption must be well designed to address and not exacerbate these issues. As Drewnowski and Darmon (p. 265, 2005) note, 'encouraging low-income families to consume healthier but more costly foods to prevent future disease can be construed as an elitist approach to public health'.

Recognising the role of food infrastructures and environments should be an important part of policy design. A recent UN report found that in the UK '1 in 3 children are now overweight or obese when they leave school with children from poor areas twice as likely to be obese' (UNICEF UK, 2019), attributing this to the rise of 'food swamps' which are disproportionately found in less affluent regions. 'Food swamps', areas with many fast-food services, or 'food deserts', areas without access to shops selling healthier produce, present increasing challenges to UK public health. A key factor in both these phenomena is the price of food, where either access to cheap healthy food is limited or there is a concentrated source of cheap unhealthy food.

In encouraging reduced meat consumption, there is a need to avoid perverse incentives created by simplistic pricing strategies; appropriate alternatives should be incentivised to avoid calorie substitution with less nutritious goods. A blanket carbon tax on food could paradoxically incentivise consumption of ultra-processed and unhealthy goods, since as Drewnowski et al. (p. 188, 2015) found in an LCA study, some of the lowest emissions values 'were associated with foods of low nutritional value, including sweets.' Saunders et al. (2015) also draw attention to the need to use planning tools to regulate the siting of fast food outlets as part of a raft of measures which avoid adverse economic impacts on low income groups. Policy should emphasise a 'value for calories' approach, that is, incentivise uptake of foods which offer the highest nutritional quality per calorie whilst remaining mindful of consumer preferences, pricing, and potential rebound effects. This highlights that it is not the strategy itself which could adversely affect certain groups, but the nature of policy instruments enacted to implement the strategy.

4.4.2. Dietary transitions

Dietary transitions reduced annual territorial emissions by between 22 and 44%. The potential reductions are contingent on the assumptions of logistic change (see SI, equation S(1)), and it is feasible that a faster (or indeed slower) rate of transition between diet types could occur than is modelled. A notable feature of the scenario was the large projected emissions reductions in the BAU case. Whether or not this pattern of change is ultimately sustainable is yet another unknown however, and many attribute recent trends to the phenomenon of dietary 'fads'. This assumption is constrained by the data availability around recent dietary change which at best relies on small sample sizes, at worst anecdotal evidence.

The large potential of dietary transitions is highlighted in Fig. 9, which suggests the impact of modal shifts between food categories comprising the national average diet. Transitions from the most high-impact groups, mainly animal-proteins, realise much of the total mitigation. A perhaps surprising result is the contribution of processed meats. Due to the classification system adopted, processed meats encompass both ruminant and monogastric meats, defined by how the final product is bought (i.e. as a burger irrespective of what meat constitutes it). This group is also consumed in greater volumes than the other specific meat categories, partially explaining the trend. This indicates that reducing the consumption of processed meats could be a priority strategy in addressing food emissions, supported by the negative health impacts of this product type (Willett et al., 2019).

Dietary change is problematic to encourage as choice in diet is commonly perceived as a fundamental human right. However, current attitudes have created policy space for greater intervention by creating an environment of acceptability around reduced meat diets. Green Alliance state the importance of 'mandatory procurement standards for caterers in public institutions', which would start to normalise reduced meat intake amongst a more diverse demographic (p. 29, 2019). Greater support for research and innovation in alternative proteins could also stimulate the development of meat alternatives which are more attractive to consumers, since the WRI (2019, p. 88) suggests the need to 'sell a compelling benefit' for alternative foods.

Food labelling has also often been cited as an important tool for nudging pro-environmental food preferences through information provision (Gadema and Oglethorpe, 2011), although there is limited empirical evidence. There is currently discussion over implementation of 'climate labelling' in Denmark (Quackenbush, 2018). Additionally, the alternative protein manufacturer Quorn has recently announced plans to add carbon labelling to their packaging, verified by the Carbon Trust (Smithers, 2020). Some argue that shifting from voluntary to mandatory environmental labelling would promote more sustainable consumption (Poore, 2018).

Another strand of information provision is the creation of 'pro-environmental dietary guidelines', as have been adopted in Sweden, Brazil and the Netherlands (p. 8, Röös et al., 2017). Röös et al. (2017) also report that there has been initial modelling of meat and dairy taxes in some countries. Whether dietary guidelines would translate into tangible change on the ground however, and whether the modelled taxes are ever legislated, are unknowns. Implementation of such schemes whilst public attitude is favourable should be a priority in the UK nonetheless.

It is debatable whether informational tools could achieve a scale of mitigation in line with climate commitments. A contentious strategy often debated in the food sector is differential taxation of more emissions-intensive goods (Chalmers et al., 2016). There is the potential that if the UK disincentivised meat consumption through tax meat *exports* would grow as a rebound, which may displace inefficient production elsewhere or else simply encourage greater absolute global consumption. Similarly, the economic implications for the meat and dairy industry in the UK would need to be carefully considered. Taxation strategies ignoring the impact of consumption-based meat and dairy emissions could put UK agriculture at risk of carbon leakage, with negative overall impacts for global emissions from the sector given the relative production efficiencies and environmental standards of UK agriculture. New applications of blockchain technologies to the food supply chain could promise effective tracing of the environmental impacts of

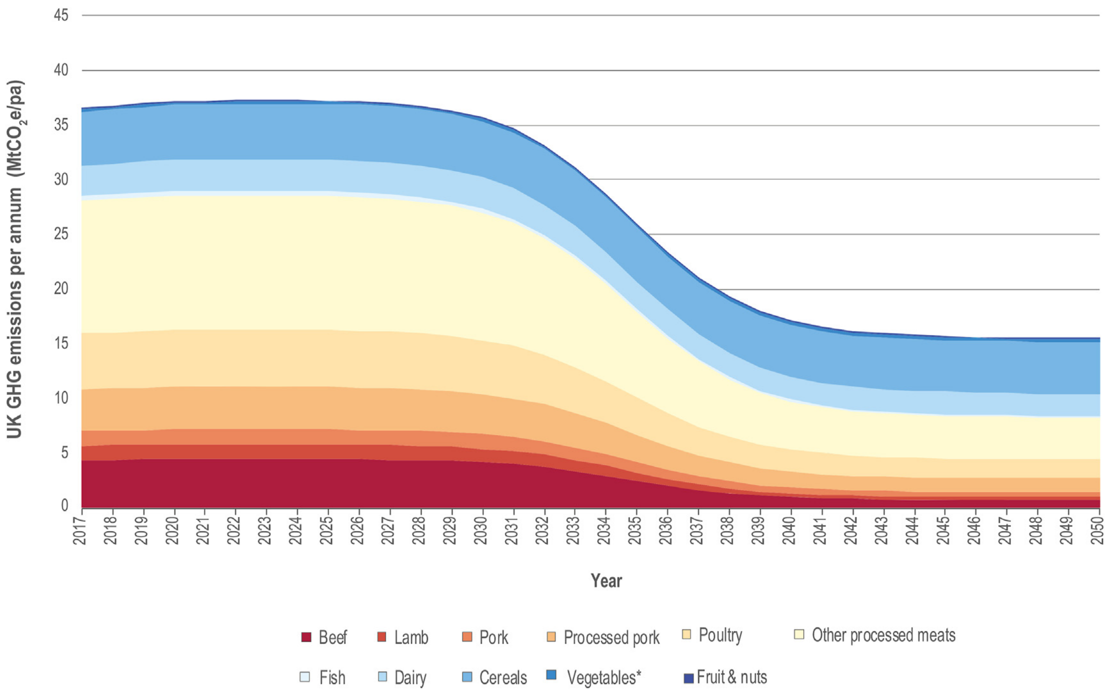

Fig. 9. Time series change in emissions by headline product groups in the high ambition case. *Vegetables includes vegetable fats and alternative proteins.

imported goods, potentially helping to frame UK food policy in a globally responsible way (Kamilaris et al., 2019).

4.4.3. Food waste reduction

The food waste scenario achieved emissions reductions of 4% (cumulative, 2017–2050). This is somewhat comparable to the reductions achieved in Bryngelsson et al. (2016). However, the feasibility of reducing food waste rates to zero avoidable across the supply chain is questionable. This is true of current technologies and solutions employed to address food waste, but future innovation may enable greater reductions. Limitations in the approach to food waste modelling include the assumption of a 'flat' rate of reduction across all food groups (relative to their current waste rates), and of a linear trend in reductions being achieved. In reality, a more irregular pattern of reductions could be followed, particularly in the harder-to-abate sections of the food supply chain. The seemingly minimal contribution from FWR may be explained by only consumer waste reduction being modelled. Whole chain waste reduction could possibly achieve greater mitigation. However, the results are largely consistent with the relative scale of reductions achieved by FWR identified in Ivanova et al. (2020), and against the potentials from dietary transitions.

Policy on FWR is relatively well developed in the UK, in some part due to a framing of the issue as a 'moral scandal' (p. 4, HM Government, 2018). According to WRAP's 'waste hierarchy', stopping the creation of waste in the first place is most preferable (p. 34, CCC, 2018). Green Alliance propose mandatory 'separate food waste collections' to reduce waste rates in England (p. 29, Green Alliance, 2019).

A further consequence of FWR could be the changed availability of biomass for downstream energy production (e.g. bioenergy via anaerobic digestion). This could negatively affect stocks of biomass resources available to offset use of fossil fuels in energy production. However, as part of a broader transition to a net zero economy, alternative renewable sources should be increasingly available to fulfil this purpose.

4.5. Limitations and future research directions

Due to the complexity of modelling the food system several simplifying assumptions were made. There may be some discrepancies between other estimates of emissions from total agricultural production given our analysis is based on bottom-up estimates of calorific consumption. Uncertainties exist in the analysis in the form of assumption uncertainties and uncertainties in the datasets used. Uncertainty analysis of MRIO models has shown that uncertainty is attributable to underlying differences in the use of production-based accounts rather than in methodology for constructing the consumption-based account (Peters et al., 2012). Lenzen et al. (2010) conduct a comprehensive uncertainty analysis of UKMRIO. A full sensitivity analysis was not undertaken in the current work as the paper aims to present scenarios, rather than projections or forecasts. There is inherent uncertainty in outlining narratives of future change, represented by the range of scenarios applied. Therefore, an extended sensitivity analysis was beyond the scope of the present work. If the work was extended to explore one of the scenarios in depth a sensitivity analysis would be a valuable addition.

Other extensions to the modelling could involve selectively changing rates of reduction in consumption and waste per food group in the calorific intake and food waste scenarios, since this is likely to vary by product. The modelling of dietary transitions could also include representing change on a generational basis. That is, by assessing the likelihood of different age groups following certain diets and the typical longevity of such choices. A refinement to the food waste modelling could involve considering the linkages between reduced waste rates and consumption and expenditure changes.

Further extensions to the analysis could include the greater consideration of alternative proteins such as lab-grown meats, insect and algal proteins, which have a unique impact given their industrial production but potential energy intensity. The impact of dietary transitions on employment and the value added of the food and drink sector, could be parallel areas of interest.

The policy options required to achieve the scale of mitigation outlined in the scenarios should also be considered further. For instance, insights from behavioural theory can valuably inform the design of policy for dietary change. The evidence base of existing policies and the nature of future interventions required is limited however, as outlined by Joyce et al. (2012). Atkins and Michie (p. 164, 2015) argue that previous approaches to designing interventions have been 'non-systematic' and that they have been 'essentially guessing at what might be the solution without having understood the problem.' A recent 'systematic mapping of behavioural interventions' for sustainable food consumption (Reisch et al., 2021) could suggest a way forward to design suitably ambitious policy informed by behavioural theory.

5. Conclusion

The analysis has revealed that simple and available demand-side actions have transformative potential in mitigating UK food emissions. We find that demand-side change could achieve a reduction of over a half in the UK's annual GHG emissions between 2017 and 2050, regardless of prospective technological changes to production efficiencies. Dietary change represents particular potential for mitigation, followed by guideline calorific intakes and food waste reduction. Demand-side change is crucial given projected growth in the UK population to 2050, which suggests that current levels of per capita consumption are unsustainable.

Demand-side change would have the further benefit of acting on the consumption-based impact of the UK's food demand, which is important given that the UK has a historic and global responsibility to decarbonise further and faster. Notwithstanding the simplifications of the analysis, it has shown that with ambitious mitigation the UK food system could be more in line with a net zero future, to a significant extent. The compatibility of future food emissions with the UK's net zero 2050 target is ultimately dependent on the steps taken by the rest of the UK economy to decarbonise in line with 1.5 °C, but it can be seen that food can make an important contribution to mitigation, even discounting additional benefits from reduced LUC and increased CO_2 removals potential. Although public receptivity to diet change currently appears high in the UK, this should not be taken as a given, and there is need for a significant upscaling of policy effort. Given the scale of the challenge, no option can be left unused to capture all possible savings. There is also need to recognise the significant distributional issues of the UK food system, for instance food poverty, in designing equitable policy around sustainable consumption. Similarly, demand-side action on consumption should not be assumed as the sole responsibility of *consumers*.

The analysis has indicated that demand-side action should constitute a core part of the UK's mitigation strategy for the food sector, and that implementing these changes through carefully designed distributive policy could enable a more sustainable, just, and healthy environment and society.

CRediT authorship contribution statement

Alice Garvey: Methodology, Formal analysis, Investigation, Writing - original draft. **Jonathan B. Norman:** Methodology, Writing - review & editing, Supervision. **Anne Owen:** Resources, Formal analysis, Writing - review & editing. **John Barrett:** Conceptualization, Writing - review & editing, Project administration.

Declaration of competing interest

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

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Appendix A. Supplementary data

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References

Atkins, L., Michie, S., 2015. Designing interventions to change eating behaviours. Proc. Nutr. Soc. 74 (2), 164–170. https://doi.org/10.1017/S0029665115000075.

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, D., Williams, A., 2010. How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050. WWF.

Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C.A., 2014. Importance of food-demand management for climate mitigation. Nat. Clim. Change 4, 924–929. https://doi.org/10.1038/nclimate2353.

Barrett, J., Peters, G.P., Wiedmann, T., Scott, K., Lenzen, M., Roelich, K., Le Quere, C., 2013. Consumption-based GHG emission accounting: a UK case study. Clim. Pol. 13, 1–19. https://doi.org/10.1080/14693062.2013.788858.

Behrens, P., Kiefte-de Jong, J.C., Bosker, T., Rodrigues, J.F.D., de Koning, A., Tukker, A., 2017. Evaluating the environmental impacts of dietary recommendations. Proc. Natl. Acad. Sci. U. S. A 114, 13412–13417. https://doi.org/10.1073/pnas.1711889114.

Bingham, S.A., Goldberg, G.R., Coward, W.A., Prentice, A.M., Cummings, J.H., 1989. The effect of exercise and improved physical fitness on basal metabolic rate. Br. J. Nutr. 61 (2), 155–173. https://doi.org/10.1079/BJN19890106.

Blake, L., 2014. People, Plate and Planet: the Impact of Dietary Choices on Health, Greenhouse Gas Emissions and Land Use. Centre for Alternative Technology.

Bradbury, K.E., Tong, T.Y.N., Key, T.J., 2017. Dietary intake of high-protein foods and other major foods in meat-eaters, poultry-eaters, fish-eaters, vegetarians, and vegans in UK biobank. Nutrients 9, 1317. https://doi.org/10.3390/nu9121317.

Bryngelsson, D., Wirsenius, S., Hedenus, F., Sonesson, U., 2016. How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture. Food Pol. 59, 152–164. https://doi.org/10.1016/j.foodpol.2015.12.012.

Caldeira, C., de Laurentiis, V., Corrado, S., van Holsteijn, F., Sala, S., 2019. Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. 149, 479–488. https://doi.org/10.1016/j.resconrec.2019.06.011.

Camanzi, L., Alikadic, A., Compagnoni, L., Merloni, E., 2017. The impact of greenhouse gas emissions in the EU food chain: a quantitative and economic assessment using an environmentally extended input-output approach. J. Clean. Prod. 157, 168–176. https://doi.org/10.1016/j.jclepro.2017.04.118.

Chalmers, N., Revoredo-Giha, C., Shackley, S., 2016. Socioeconomic effects of reducing household carbon footprints through meat consumption taxes. J. Food Prod. Market. 22, 258–277. https://doi.org/10.1080/10454446.2015.1048024.

Clapp, J., 2017. Food self-sufficiency: making sense of it, and when it makes sense. Food Pol. 66, 88–96. https://doi.org/10.1016/j.foodpol.2016.12.001.

Clark, M., Tilman, D., 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ. Res. Lett. 12 https://doi.org/10.1088/1748-9326/aa6cd5.

Climate Change Committee, 2019. Reducing UK Emissions: 2019 Progress Report to Parliament. https://www.theccc.org.uk/publication/reducing-uk-emissions-2019-progress-report-to-parliament/. (Accessed 19 June 2020).

Climate Change Committee, 2018. Land Use: Reducing Emissions and Preparing for Climate Change. https://www.theccc.org.uk/publication/land-use-reducing-emissions-and-preparing-for-climate-change/. (Accessed 19 June 2020).

Department for Environment Food and Rural Affairs, 2018. Family Food 2016/17: UK Household Purchases. https://www.gov.uk/government/publications/family-food-201617/purchases. (Accessed 19 June 2020).

Department for Environment Food and Rural Affairs, 2019. Food Statistics in Your Pocket: Global and UK Supply. https://www.gov.uk/government/publications/food-statistics-pocketbook/food-statistics-in-your-pocket-global-and-uk-supply. (Accessed 19 June 2020).

Department for Environment Food and Rural Affairs, 2011. Making the Most of Packaging: A Strategy for a Low-Carbon Economy. https://www.gov.uk/government/publications/making-the-most-of-packaging-a-strategy-for-a-low-carbon-economy. (Accessed 19 June 2020).

Drewnowski, A., Darmon, N., 2005. The economics of obesity: dietary energy density and energy cost. Am. J. Clin. Nutr. 82, 265S–273S. https://doi.org/10.1093/ajcn/82.1.265S.

Drewnowski, A., Rehm, C.D., Martin, A., Verger, E.O., Voinnesson, M., Imbert, P., 2015. Energy and nutrient density of foods in relation to their carbon footprint. Am. J. Clin. Nutr. 101, 184–191. https://academic.oup.com/ajcn/article/101/1/184/4564263.

EAT-Lancet Commission, 2019. The EAT-Lancet Commission on Food, Planet, Health. https://eatforum.org/eat-lancet-commission/. (Accessed 5 September 2019).

Fontana, L., Villareal, D.T., Weiss, E.P., Racette, S.B., Steger-May, K., Klein, S., Holloszy, J.O., Washington University School of Medicine CALERIE Group, 2007. Calorie restriction or exercise: effects on coronary heart disease risk factors. A randomized, controlled trial. Am. J. Physiol. Endocrinol. Metab. 293 (1), 197–202. https://doi.org/10.1152/ajpendo.00102.2007.

Food and Agriculture Organization, 2020. FAOSTAT - New Food Balances. http://www.fao.org/faostat/en/#data/FBS. (Accessed 6 April 2020).

Gadema, Z., Oglethorpe, D., 2011. The use and usefulness of carbon labelling food: a policy perspective from a survey of UK supermarket shoppers. Food Pol. 36, 815–822. https://doi.org/10.1016/j.foodpol.2011.08.001.

Garnett, T., 2014. Three perspectives on sustainable food security: efficiency, demand restraint, food system transformation. What role for life cycle assessment? J. Clean. Prod. 73, 10–18. https://doi.org/10.1016/j.jclepro.2013.07.045.

Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain?). Food Pol. 36, S23–S32. https://doi.org/10.1016/j.foodpol.2010.10.010.

Garnett, T., 2009. Livestock-related greenhouse gas emissions: impacts and options for policy makers. Environ. Sci. Pol. 12, 491–503. https://doi.org/10.1016/j.envsci.2009.01.006.

Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health and the environment. Science 361, 5324.

González, A.D., Frostell, B., Carlsson-Kanyama, A., 2011. Protein efficiency per unit energy and per unit greenhouse gas emissions: potential contribution of diet choices to climate change mitigation. Food Pol. 36, 562–570. https://doi.org/10.1016/j.foodpol.2011.07.003.

Green Alliance, 2019. Cutting the Climate Impact of Land Use. https://www.green-alliance.org.uk/Cutting_the_climate_impact_of_land_use.php. (Accessed 19 June 2020).

Green Alliance, 2018. Less in, More Out: Using Resource Efficiency to Cut Carbon and Benefit the Economy. https://www.green-alliance.org.uk/less_in_more_out.php. (Accessed 19 June 2020).

Grübler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., De Stercke, S., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3, 515–527. https://doi.org/10.1038/s41560-018-0172-6.

Han, T.S., Tajar, A., Lean, M.E.J., 2011. Obesity and weight management in the elderly. Br. Med. Bull. 97 (1), 169–196. https://doi.org/10.1093/bmb/ldr002.

Hancox, D., 2018. The Unstoppable Rise of Veganism: How a Fringe Movement Went Mainstream. The Guardian. https://www.theguardian.com/lifeandstyle/2018/apr/01/vegans-are-coming-millennials-health-climate-change-animal-welfare. (Accessed 19 June 2020).

Harper, H., Hallsworth, M., 2016. Counting Calories: how under-reporting can explain the apparent fall in calorie intake. The Behavioural Insights Team. https://www.bi.team/publications/counting-calories-how-under-reporting-can-explain-the-apparent-fall-in-calorie-intake/. (Accessed 19 June 2020).

Hm Government, 2018. Our Waste, Our Resources: A Strategy for England. https://www.gov.uk/government/publications/resources-and-waste-strategy-for-england. (Accessed 19 June 2020).

House of Commons Environmental Audit Committee, 2019. Our Planet, Our Health: Twenty-First Report of Session 2017-19. London.

Innovate UK, UK Research and Innovation, 2019. Transforming the Way We Produce Food: Apply for Business Funding. https://www.gov.uk/government/news/transforming-the-way-we-produce-food-apply-for-business-funding. (Accessed 15 October 2019).

IPCC, 2018. Chapter 5: Food Security. https://www.ipcc.ch/srccl/chapter/chapter-5/. (Accessed 19 June 2020).

Ipsos MORI, 2016. Vegan Society Poll Ipsos MORI. https://www.ipsos.com/ipsos-mori/en-uk/vegan-society-poll. (Accessed 6 November 2019).

Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., Creutzig, F., 2020. Quantifying the potential for climate change mitigation of consumption options. Environ. Res. Lett. 15 (9) https://doi.org/10.1088/1748-9326/ab8589 (in press).

Jones, L., 2018. Veganism: Why Is it on the up? BBC News. https://www.bbc.co.uk/news/business-44488051. (Accessed 16 November 2019).

Joyce, A., Dixon, S., Comfort, J., Hallett, J., 2012. Reducing the environmental impact of dietary choice: perspectives from a behavioural and social change approach. Journal of Environmental and Public Health 1–7. https://doi.org/10.1155/2012/978672.

Kamilaris, A., Fonts, A., Prenafeta-Boldύa, F.X., 2019. The rise of blockchain technology in agriculture and food supply chains. Trends Food Sci. Technol. 91, 640–652. https://doi.org/10.1016/j.tifs.2019.07.034.

Kanemoto, K., Moran, D., Shigetomi, Y., Reynolds, C., Kondo, Y., 2019. Meat consumption does not explain differences in household food carbon footprints in Japan. One Earth 1, 464–471. https://doi.org/10.1016/j.oneear.2019.12.004.

Lenzen, M., Wood, R., Wiedmann, T., 2010. Uncertainty analysis for Multi-Region Input-Output models – a case study of the UK's carbon footprint. Econ. Syst. Res. 22 (1), 43–63. https://doi.org/10.1080/09535311003661226.

McMichael, A.J., Powles, J.W., Butler, C., Uauy, R., 2007. Food, livestock production, energy, climate change, and health. Lancet 370, 1253–1263. https://doi.org/10.1016/S0140-6736(07)61256-2.

Meyer, P., 1994. Bi-logistic growth. Technol. Forecast. Soc. Change 47 (1), 89–102. https://doi.org/10.1016/0040-1625(94)90042-6.

Miller, R.E., Blair, P.D., 2009. Input-output Analysis: Foundations and Extensions. Cambridge University Press.

Miller, D.T., Prentice, D.A., 2016. Changing norms to change behavior. Annu. Rev. Psychol. 67, 339–361. https://doi.org/10.1146/annurev-psych-010814-015013.

Nemecek, J., Poore, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216.

NHS Digital, 2018. Statistics on Obesity, Physical Activity and Diet - England, 2018. Statistics on Obesity, Physical Activity and Diet. https://digital.nhs.uk/data-and-information/publications/statistical/statistics-on-obesity-physical-activity-and-diet/statistics-on-obesity-physical-activity-and-diet-england-2018. (Accessed 23 May 2019).

Office for National Statistics, 2019. National Population Projections: 2018-based. https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2018based. (Accessed 25 October 2019).

Owen, A., Scott, K., Barrett, J., 2018. Identifying critical supply chains and final products: an input-output approach to exploring the energy-water-food nexus. Appl. Energy 210, 632–642. https://doi.org/10.1016/j.apenergy.2017.09.069.

Peters, G.P., Davis, S.J., Andrew, R., 2012. A synthesis of carbon in international trade. Biogeosciences 9, 3247–3276. https://doi.org/10.5194/bg-9-3247-2012.

Poore, J., 2018. We label fridges to show their environmental impact – why not food? The Guardian. https://www.theguardian.com/environment/2018/oct/10/we-label-fridges-to-show-their-environmental-impact-why-not-food. (Accessed 8 January 2021).

Priestley, S., 2019. Briefing Paper: Legislating for Net Zero. London.

Public Health England, 2016. Government Dietary Recommendations: Government Recommendations for Food Energy and Nutrients for Males and Females about Public Health England 1–12. https://www.gov.uk/government/publications/the-eatwell-guide. (Accessed 19 June 2020).

Public Health England, 2019. National Diet and Nutrition Survey: Years 1 to 9 of the Rolling Programme (2008/2009 - 2016/2017): Time Trend and Income Analyses. https://www.gov.uk/government/statistics/ndns-time-trend-and-income-analyses-for-years-1-to-9. (Accessed 19 June 2020).

Quackenbush, C., 2018. Denmark Wants Food Labels to Include Environmental Impact Time. https://time.com/5419208/denmark-food-label-climate/. (Accessed 15 October 2019).

Reutter, B., Lant, P., Reynolds, C., Lane, J., 2017. Food waste consequences: environmentally extended input-output as a framework for analysis. J. Clean. Prod. 153, 506–514. https://doi.org/10.1016/j.jclepro.2016.09.104.

Reynolds, C., Piantadosi, J., Buckley, J.D., Weinstein, P., Boland, J., 2015. Evaluation of the environmental impact of weekly food consumption in different socio-economic households in Australia using environmentally extended input–output analysis. Ecol. Econ. 111, 58–64. https://doi.org/10.1016/j.ecolecon.2015.01.007.

Reisch, L.A., Sunstein, C.R., Andor, M.A., Doebbe, F.C., Meier, J., Haddaway, N.R., 2021. Mitigating climate change via food consumption and food waste: a systematic map of behavioural interventions. J. Clean. Prod. 279, 123717. https://doi.org/10.1016/j.jclepro.2020.123717.

Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D., Garnett, T., 2017. Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. Global Environ. Change 47, 1–12. https://doi.org/10.1016/j.gloenvcha.2017.09.001.

Roser, M., Ritchie, H., 2019. Food Per Person - Our World in Data. https://ourworldindata.org/food-per-person. (Accessed 16 November 2019).

Rosi, A., Mena, P., Pellegrini, N., Turroni, S., Neviani, E., Ferrocino, I., Di Cagno, R., Ruini, L., Ciati, R., Angelino, D., Maddock, J., Gobbetti, M., Brighenti, F., Del Rio, D., Scazzina, F., 2017. Environmental impact of omnivorous, ovo-lacto-vegetarian, and vegan diet. Sci. Rep. 7, 1–9. https://doi.org/10.1038/s41598-017-06466-8.

Salemdeeb, R., Bin Daina, M., Reynolds, C., Al-Tabbaa, A., 2018. An environmental evaluation of food waste downstream management options: a hybrid LCA approach. Int. J. Recycl. Org. Waste Agric. 7, 217–229. https://doi.org/10.1007/s40093-018-0208-8.

Sanjuán, N., Stoessel, F., Hellweg, S., 2014. Closing data gaps for LCA of food products: estimating the energy demand of food processing. Environ. Sci. Technol. 48, 1132–1140. https://doi.org/10.1021/es4033716.

Saunders, P., Saunders, A., Middleton, J., 2015. Living in a 'fat swamp': exposure to multiple sources of accessible, cheap, energy-dense fast foods in a deprived community. Br. J. Nutr. 113, 1828–1834. https://doi.org/10.1017/S0007114515001063.

Scott, K., Giesekam, J., Barrett, J., Owen, A., 2018. Bridging the climate mitigation gap with economy-wide material productivity. J. Ind. Ecol. 1–14. https://doi.org/10.1111/jiec.12831.

Smetana, S., Mathys, A., Knoch, A., Heinz, V., 2015. Meat alternatives: life cycle assessment of most known meat substitutes. Int. J. Life Cycle Assess. 20, 1254–1267. https://doi.org/10.1007/s11367-015-0931-6.

Smithers, R., 2020. Quorn to Be First Major Brand to Introduce Carbon Labelling. The Guardian. https://www.theguardian.com/environment/2020/jan/09/quorn-to-be-first-major-brand-to-introduce-carbon-labelling. (Accessed 19 June 2020).

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0.

Stehfest, E., Bouwman, L., van Vuuren, D.P., den Elzen, M., Eickhout, B., Kabat, P., 2009. Climate benefits of changing diet. Climatic Change 95, 83–102. https://doi.org/10.1007/s10584-008-9534-6.

The Trussell Trust, 2019. End of Year Stats - the Trussell Trust. https://www.trusselltrust.org/news-and-blog/latest-stats/end-year-stats/. (Accessed 4 May 2020).

UK Data Service, 2019. Living Costs and Food Survey. https://beta.ukdataservice.ac.uk/datacatalogue/series/series?id=2000028. (Accessed 19 June 2020).

UK Government, 2019. UK's Carbon Footprint. https://www.gov.uk/government/statistics/uks-carbon-footprint. (Accessed 19 June 2020).

UNFCCC, 2015. The Paris Agreement. http://unfccc.int/paris_agreement/items/9485.php. (Accessed 23 March 2018).

UNICEF UK, 2019. Poor Diets Damaging Children's Health. warns UNICEF. https://www.unicef.org.uk/press-releases/poor-diets-damaging-childrens-health-warns-unicef/. (Accessed 16 October 2019).

United Nations, 2019. Sustainable Development Goal 2. https://sustainabledevelopment.un.org/sdg2. (Accessed 15 October 2019).

Virtanen, Y., Kurppa, S., Saarinen, M., Katajajuuri, J., Usva, K., Mäenpää, I., Mäkelä, J., Grönroos, J., Nissinen, A., 2011. Carbon footprint of food – approaches from national input–output statistics and a LCA of a food portion. J. Clean. Prod. 19, 1849–1856. https://doi.org/10.1016/j.jclepro.2011.07.001.

Waitrose & Partners, 2019. Food and Drink Report 2018-19. https://www.waitrose.com/home/about_waitrose/the-waitrose-fooddrinkreport.html. (Accessed 19 June 2020).

Westerterp, K.R., 2013. Physical activity and physical activity induced energy expenditure in humans: measurement, determinants, and effects. Front. Physiol. 4, 90. https://doi.org/10.3389/fphys.2013.00090.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Wilson, B., 2019. Protein Mania: the Rich World's New Diet Obsession. The Guardian. https://www.theguardian.com/news/2019/jan/04/protein-mania-the-rich-worlds-new-diet-obsession. (Accessed 19 June 2020).

World Resources Institute (WRI), 2019. Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050. Washington D.C.

YouGov UK, 2017. YouGov/Eating Better Survey Results, vols. 13–14. https://yougov.co.uk/. (Accessed 19 June 2020).