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# Changes in greenhouse gas emissions from food supply in the United Kingdom

Kerry Stewart[a,b,*], Andrew Balmford[a], Pauline Scheelbeek[c], Anya Doherty[d], Emma E. Garnett[a,e]

[a] Conservation Science Group, Department of Zoology, University of Cambridge, Cambridge, CB2 3EJ, UK
[b] School of Biological Sciences, University of Reading, Whiteknights, Reading, RG6 6AS, UK
[c] Centre on Climate Change & Planetary Health, London School of Hygiene & Tropical Medicine, Keppel Street, London, WC1E 7HT, UK
[d] Foodsteps, 21-33 Great Eastern St, London, EC2A 3EJ, UK
[e] Cambridge Institute for Sustainability Leadership, University of Cambridge, Cambridge, CB2 1QA, UK

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ABSTRACT

Food systems contribute 23–42% of global greenhouse gas emissions. Reducing food system emissions is an essential component of climate change mitigation, and a system-wide approach, including production, processing, trade and demand-side transformations, will be needed. Long-term analysis of greenhouse gas (GHG) emissions of food supply is crucial for informing this transformation, and understanding the processes contributing to existing trends can reveal opportunities for future mitigation strategies. To address these needs we used data on food supply, trade and emission intensity to quantify changes in GHG emissions between 1986 and 2017 resulting from food supply in the United Kingdom (UK). Uniquely, the relative contributions of supply-side and demand-side changes to historical trends in food emissions were assessed, and the gap between current UK food consumption and EAT-Lancet recommended diets was used to estimate the additional GHG emission reductions that could be achieved by shifting to the Planetary Health Diet (PHD). It was estimated that in the UK, per-capita GHG emissions from food fell by 32% (from 4.6 $tCO_2eq$/capita to 3.1 $tCO_2eq$/capita) between 1986 and 2017. Of this 32% reduction, 21% was due to supply-side changes (a fall in emission intensity per unit of production due to increased efficiency of farming practices), 10% was due to demand-side changes (including dietary change and waste reduction), and 2% was due to changing trade patterns. Relative to the PHD, however, the average UK citizen still greatly over-consumes beef, lamb and pork, tubers and starchy vegetables and dairy products, and under-consumes vegetables, nuts, and legumes. It was estimated that by adopting the PHD, UK per capita food emissions could be reduced by a further 42% to 1.8 $tCO_2eq$/capita. These results expose the historic contributions of both supply- and demand-side changes to reductions in GHG emissions from food, and highlight the underutilised potential of dietary change in contributing to mitigation of GHG emissions from food.

## 1. Introduction

Without transformational changes to global food systems it will not be possible to limit global warming to 1.5 °C (Clark et al., 2020). Food systems are responsible for 23–42% (95% confidence range) of global greenhouse gas emissions (GHG) (IPCC et al., 2022) and if current trends continue, emissions from food are expected to increase due to rising consumption of emission-intensive foods and increasing global population (Costa et al., 2022). Alongside increases in food supply emissions, changing food consumption patterns also have implications for human health. Currently four of the top five risk factors causing loss of healthy life years are diet related (Dimbleby, 2021), and a rise in the demand for red and processed meat and foods with low nutritional value has been associated with an increase in prevalence of non-communicable diseases such as obesity (Bodirsky et al., 2020) and heart disease (Chung et al., 2021). Global food system change is needed for the environment and human health.

Mitigation of food system emissions can be achieved through supply- or demand-side measures. Supply-side measures aim to reduce the emission intensity of food production through practices such as reducing

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* Corresponding author. School of Biological Sciences, University of Reading, Whiteknights, Reading, RG6 6AS, UK.
*E-mail address:* kerrysmith189@gmail.com (K. Stewart).

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fertilizer run off and increasing energy-use efficiency (OECD, 2019), while demand-side measures aim to reduce emissions through waste reduction and dietary change (Garvey et al., 2022). Understanding the relative contributions of supply- and demand-side changes to long-term trends in food supply emissions provides crucial insights for devising emissions reduction scenarios, essential for identifying policy levers for further emissions mitigation. As dietary change has implications for human health, identifying measures which provide emissions reductions alongside net neutral or beneficial health outcomes is vital (Mertens et al., 2017). Quantifying the mitigation potential of dietary change, when aligning with these requirements, is key for determining the opportunity posed by demand-side measures for future emission reduction strategies.

## 2. Literature review

Supply-side measures have contributed significantly to reduction in GHG emissions from food supply in the past. Emissions have been increasingly decoupled from production due technological innovation, regional specialisation and intensification (Bennetzen et al., 2016). Bennetzen et al. (2016) found that between 1970 and 2007 the emission intensity of crop production (per kg of product) declined by 38% and emission intensity of livestock production declined by 44%. While emissions reductions are expected to continue until at least 2050, it is projected that these declines will slow (Bennetzen et al., 2016). Valin et al. (2013) found that even if yield gaps of crops were halved and of livestock were reduced by 25%, this would only offer an 8% reduction in agricultural and land use change emissions. As such, a diverse approach to mitigating food system emissions including both supply-side and demand-side measures will be needed (Poore and Nemecek, 2018).

To-date policy mechanisms for reducing food system emissions have largely focused on agricultural production, with demand-side measures, particularly those surrounding dietary change, receiving less attention (Garvey et al., 2022). An increasing share of animal-based products (meat, fish and dairy) in diets has been associated with increased GHG emissions of food supply (Whitton et al., 2021) and in the last few decades post-consumer waste (waste after food purchase) has increased (Parfitt et al., 2010). Despite this, the relative contribution of demand-side changes to historical trends in GHG emissions from food is largely unknown. Garvey et al. (2021) highlighted the opportunity that dietary changes provide for food emissions mitigation and discussed the challenge of public perception when encouraging dietary change. Concerns about health trade-offs impedes use of policies which encourage dietary change, and bold changes, such as encouraging a complete shift to plant-based food are often unpopular (Garvey et al., 2021). Acceptability is a major factor in influencing the success of demand-side measures and must be considered in policy planning.

One way to quantify the opportunity provided by demand-side changes is to consider the effects of consumer adoption of references diets. The Planetary Health Diet (PHD) is a healthy and sustainable diet outlined by the EAT-Lancet Commission (2019). It is estimated that change from current diets to the PHD will result in major health benefits, avoiding around 11 million adult deaths per year (EAT-Lancet Commission, 2019). The PHD recommends an ambitious reduction in meat consumption, greater than diets such as the Eatwell Guide in the UK (Scheelbeek et al., 2020a), but does not recommend an entirely plant-based diet for everyone (EAT-Lancet Commission, 2019). Permitting limited consumption of meat and dairy may make the PHD more acceptable for some, which could enhance its uptake (Garvey et al., 2022). As the PHD is designed to optimise planetary and human health, comparison of current consumption to the PHD can reveal potential GHG emission reductions achievable through dietary change if adopted.

When comparing the impact of supply- and demand-side changes on food supply emissions it is necessary to consider the impact of trade. Changing trade patterns can be driven by both supply- and demand-side changes due to changes in production efficiency influencing the price and availability of produce, and changes in demand for food products. Due to an increasingly diversified diet, there has been an increase in demand for non-domestic produce, particularly fruit and vegetables (Scheelbeek et al., 2021). Increase in trade has been linked to the increasing emissions of food supply, particularly as a result of sourcing of beef from Latin America (Schmitz et al., 2012). However, Godfray et al. (2010) report that alongside these increases, globalisation might increase efficiency of production due to regional specialisation. Understanding the impact of trade patterns on GHG emission of food supply is necessary to provide information on whether eating local is (as widely assumed) a more sustainable option (Edwards-Jones, 2010). By accounting for trade, it is possible to take a consumption perspective (Garvey et al., 2021). This ensures that the emissions of non-domestic produce are included, providing a holistic assessment of changes in food supply emissions.

In this study, data from the UK were used to assess the relative effects of changes in emissions intensity, trade and demand on trends in food system emissions and explore the emissions reductions afforded by adoption of the PHD. To our knowledge no one has yet assessed the relative contribution of supply and demand side changes to historical trends in GHG emission from food. The UK is an appropriate study country as there are reasonably robust data on trends in food supply (Smith et al., 2021), and 35% of total GHG emissions come from food and drink (Forbes et al., 2021). There is evidence that emissions from UK food supply are in decline due to declining emissions intensity (Forbes et al., 2021), changes in trade patterns (de Ruiter et al., 2016), and dietary shifts (Foster and Lunn, 2007), but their relative importance has yet to be elucidated. By bringing together data on UK dietary trends, food trade and production intensity, the scale of reductions in food system emissions was quantified and the potential for future progress identified in two steps. First, emissions changes under existing trends (between 1986 and 2017) were analysed and the relative contribution of changes in emission intensity, trade and demand to this trend were found. Secondly, the additional mitigation potential of UK population-wide shift from current diets to diets in line with the PHD guidelines was calculated. This provides unique insights into the scale of emissions reductions possible with adoption of a healthy, sustainable, and flexible reference diet, rather than focussing on sustainability alone. By doing this we aimed to provide the information needed to assess the potential contribution of demand-side measures to future GHG emission mitigation strategies of food supply.

## 3. Methods

### 3.1. Greenhouse gas emissions of UK food supply between 1986 and 2017

### 3.1.1. Overview

Food balance sheets, produced by FAO, were used to calculate annual supply of food products to the UK. FAO is a specialized agency of the United Nations that provides free access to fifty years of food and agriculture data. They are unbiased and have the capacity to gather, collate and standardise data on a national level across the world. Due to their accessibility, reliability and comprehensiveness FAO data are widely used in food systems research (Shukla et al., 2019). The breadth and quality of FAO data is unparalleled. The time-period covered enables assessment of long-term trends, without which national comparisons of temporal changes in food production and trade would be extremely difficult. The documentation and standardisation procedures of FAOSTAT are essential for ensuring the accuracy and appropriate use of these data and set the standard for data collation and management in food system science.

FAO data record the quantity of food available to buy (food supply) as opposed to food purchases. This is appropriate as it matches the stage of the food production system measured by GHG emissions data. Data on GHG emissions of food production were obtained from Poore and Nemecek (2018), Audsley et al. (2009) and Gephart et al. (2021). Where

Poore and Nemecek (2018) values were used, continent-specific environmental impact scores for food products were calculated. For a given continent (for example, North America), life cycle assessments listed in Poore and Nemecek (2018) were selected based on their country of origin (for example, USA, Canada). A weighted average of these studies was calculated using the study weighting factors provided in Poore and Nemecek (2018) (intended to weight studies based on representativeness) to produce the final environmental impact score for that continent. GHG emissions of fish and seafood were calculated using data from Gephart et al. (2021). Where multiple seafood categories in Gephart et al. (2021) data were applicable for one commodity balance category (for example shrimp and lobster for Crustaceans) a weighted average was calculated using catch statistics from FAO Yearbook of Fishery and Aquaculture Statistics (FAO, 2021d). For fish and seafood where supply was obtained from both aquaculture and wild caught fish, a weighted average of emission intensity data was calculated using data on the proportion of aquaculture and wild catch (FAO, 2021d). Temporal changes in emissions intensity (obtained from the FAO [FAO, 2021c]) were applied. To our knowledge, FAO provide the only source of data on national changes in emission intensity over decadal time periods, across multiple food groups. As such these data were essential for accounting for temporal changes in emission intensity in this analysis. Emissions of all food types were summed to determine how total GHG emissions from the UK food system have changed between 1986 and 2017. This period was chosen because of the availability of food balance sheets (available for 1961 to 2018), data from the Detailed Trade Matrix (available between 1986 and 2018), and data on emission intensity (available between 1961 and 2017). All data used in this study are freely downloadable from cited sources. The method for estimating GHG emissions of UK food supply is summarised in Fig. 1.

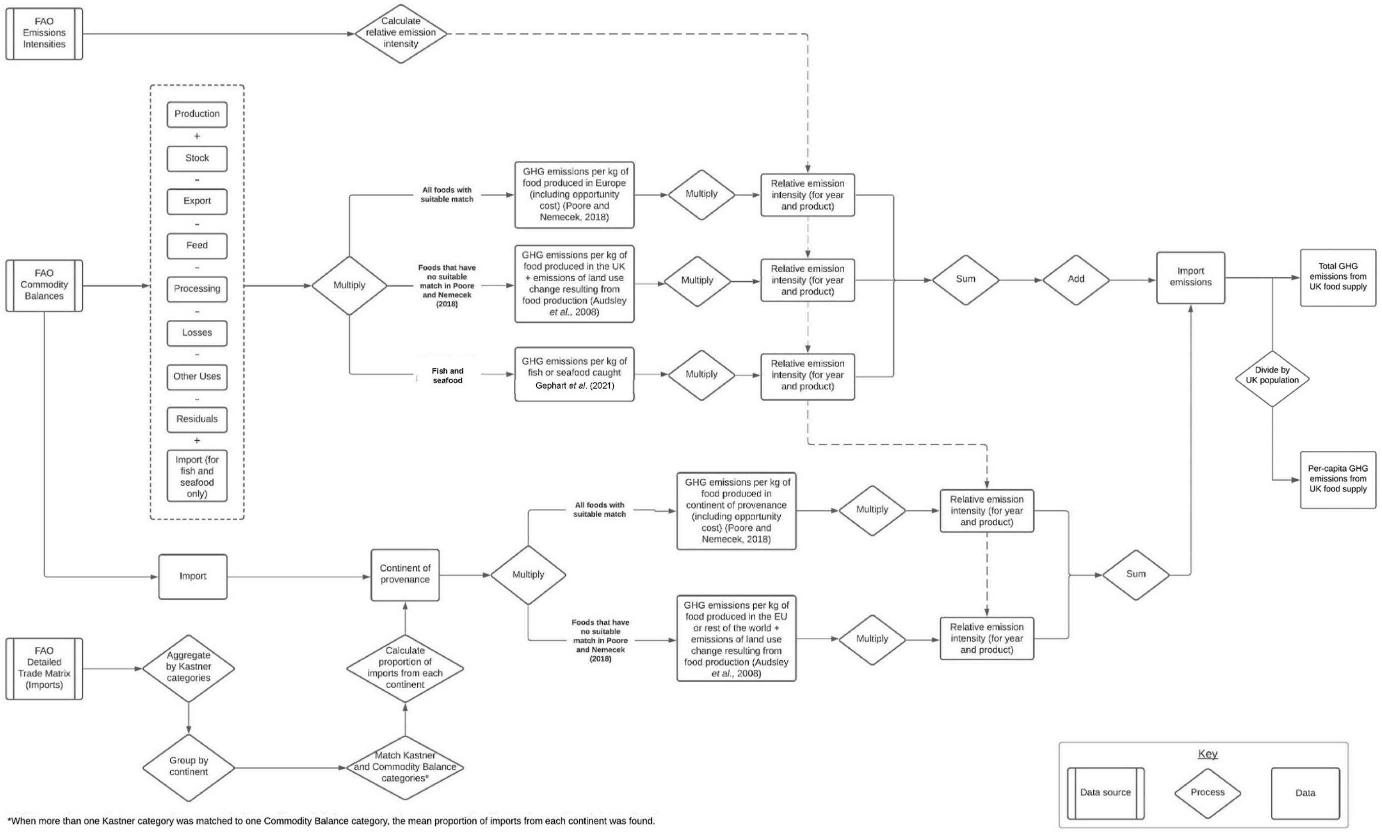
### 3.1.2. Calculating food supply

The FAO compile, check and standardise data from national statistics on domestic food supply – the quantity of food available to buy (FAOSTAT; FAO, 2017). Food supply ($S$) was calculated as shown in equation (1) (all terms in t/y).

$$S = p + i + \beta \times v - e - f - l - c - d - o - r \quad (1)$$

Where $p$ is production, $i$ is imports, $v$ is stock variation, $e$ is exports, $f$ is supply for feed, $l$, is losses, $c$ is production lost in processing, $d$ is production used for seed and $o$ is the quantity used for uses other than human consumption and $r$ is residuals. Due to differences in stock reporting after 2014, $\beta$ was 1 before 2014 and -1 from 2014 onwards. Data on the quantity of food produced, imported (including country of provenance), exported, stocked, lost, used for feed and other purposes, and residuals, are provided by FAOSTAT as Commodity Balances (FAO, 2021b).

FAO updated their methodology for reporting food supply quantities in 2014. The primary change was the shift from using 2015 United Nations Development Programme (UNDP) population data (used before 2014) to using updated 2019 UNDP population data (FAO, 2021b). Further to this, changes to calculation of stock quantities, feed, losses and residuals affect estimations of food supply, such that values estimated by the old and new methodology differ. To account for this, data between 1986 and 2009 was adjusted to align with the new methodology (data available from 2010 onwards). The FAO produced commodity balances using both the old and new methodology between 2010 and 2013, which can be used to create mean offset ratios. To do this, food supply excluding imports (i.e. that resulting from production, from stock variation, exports, feed, losses, production, loss in processing, use for seed, use for non-food and residuals) was calculated according to equation (1), for each food category and each year between 2010 and 2013 using both the new and the old methodology. For each food category, the mean offset across the three years was calculated. Quantities of food supply excluding imports between 1986 and 2009 were



*When more than one Kastner category was matched to one Commodity Balance category, the mean proportion of imports from each continent was found.

**Fig. 1.** Summary of method used to calculate total greenhouse gas (GHG) emissions from UK food and drink consumption.

adjusted by multiplying these values by the associated offset ratio. Imports were adjusted separately because the difference in quantities in the old and new methodologies varied between food components (production, imports, stock variation and other arguments of equation (1)), and emissions resulting from imports were calculated separately (to account for trade, explained in more detail in Section 3.1.4). For each food type mean offset ratios of imports were calculated and multiplied by import values between 1986 and 2009 to produce adjusted import quantities. The way of reporting stocks was also changed when the FAO methodology was updated, so that a positive value now indicates an increase in stock quantity, whereas previously a positive value indicated a decrease in stock quantity.

For *'Oilcrops, Other'* and *'Cottonseed Oil'*, summing the components of food supply (equation (1)) gave a negative value for food supply in some years (specified in Table S3). It is impossible that food supply is negative in reality, so published values of food supply from FAOSTAT (FAO, 2021b) were used rather than calculating food supply from the components listed in equation (1). Values for other food groups and years were consistent with a zero or positive food supply when calculated according to equation (1).

Data provided by the FAO on the continent of provenance of imports (Detailed Trade Matrix) are produced following different food categorisations (for definitions see Table 1) than those on food supply (Commodity Balances). For example, data on supply of bovine meat are reported in the Commodity Balances as *'Bovine meat'* yet in the Detailed Trade Matrix as an aggregation of '*Meat, beef and veal sausages*', '*Meat, beef* preparations', '*Meat, cattle*' and '*Meat, cattle, boneless (beef & veal)*'. It was necessary to transpose between categorisations used in Commodity Balances and in the Detailed Trade Matrix. This was done using the definitions provided by FAOSTAT (FAO, 2021b) and assisted using aggregations provided by Kastner et al. (2011) (hereafter referred to as Kastner categories, Table 1). This simplified the process of accounting for non-UK food production and improved the accuracy of calculating total GHG emissions across the whole diet (more detail given in Table S1). The proportion of imports from each continent was determined for each Kastner category. Where Commodity Balance categories were matched to more than one Kastner category (Table S1) the mean proportion of imports for each food supply category was found. As trade data does not include fish and seafood this analysis did not account for spatial differences in emission intensity of fish and seafood production between countries. As reported by Kastner et al. (2011), the FAO Detailed Trade Matrix gives the last destination of food before import to the UK, not necessarily the country of production. Exports were assumed to be produced in the UK. Taken together, these limitations mean findings described here rely on an approximation of the location of production. Despite this, FAO data on trade have unique resolution as they are broken down by year, country and food type, which enables a comprehensive assessment of the impact of trade patterns on UK food GHG emissions that would not be possible if this data were not available.

**Table 1**
Descriptions of food categorisations used in this analysis. Multiple food categorisations were necessary due to different categorisations of food types in source data (Commodity Balances [FAO, 2021b], Detailed Trade Matrix [FAO, 2021a] and Planetary Health Diet (EAT-Lancet Commission, 2019) (see Section 2.2).

| Type | Description |
|---|---|
| Commodity Balance categories | Food categories used by FAO for data on food supply. GHG emissions were calculated for each Commodity Balance category (equation (2)). |
| Detailed trade matrix categories | Food categories used by FAO for data on continent of provenance of imports. |
| Kastner categories | Published by Kastner et al. (2011). Kastner categories were used to transpose between Commodity Balance categories and Detailed trade matrix categories. We summed the quantity of imports from each continent across detailed trade matrix categories for each Kastner category to find the proportion of imports originating from each continent. Kastner categories were then matched to Commodity Balance categories, to find the proportion of imports from each continent for each Commodity Balance category. |
| Assigned categories | Commodity Balance categories were aggregated into broad food groups to aid presentation of results. |
| Planetary Health Diet categories | Food categories used in the Planetary Health Diet. Planetary Health Diet categories were used to compare UK food supply to the Planetary Health Diet. |

### 3.1.3. Integrating changes in emission intensity over time

Poore and Nemecek (2018), Audsley et al. (2009) and Gephart et al. (2021) provide emission intensity data for specific points in time, however emission intensity is changing (Bennetzen et al., 2016). Emission intensity data are provided by the FAO over the time period studied (FAO, 2021c). For each year FAO emission intensity was divided by that in 2005 for food types where Poore and Nemecek (2018) emissions data were used (Poore and Nemecek [2018] compiled life cycle assessments to give GHG emissions estimates for the year 2005) and by that in 2008 for food types where Audsley et al. (2009) emissions were used (Audsley et al. (2009) conducted life cycle assessments for the year 2008), to give relative emission intensity. GHG emissions were multiplied by the relative emission intensity for each food type and year. There were insufficient data to incorporate changing emission intensity for fish and seafood products. Milk included cow, goat and sheep's milk but cow's milk constituted the majority (98%; Gerosa and Skoet, 2012) so *'Milk, whole cow'* was deemed a suitable category to define changes in emission intensity over time. Changes in emission intensity only refer to changes within the on-farm stage, but these were assumed to be representative of changes at later stages in production. As emissions from land use change and pre- and post-production in the UK both declined over the time period (in alignment with farm-stage emissions), and total GHG emissions from farm-gate processes were responsible for 61% of food supply emissions (up to retail stage), this is expected to be a limited source of error.

### 3.1.4. Total and per capita GHG emissions

Total GHG emissions in $CO_2$eq, $EM_{\text{tot}}$ (t/y), were calculated as shown in equation (2):

$$EM_{\text{tot}} = (GHG_{\text{EU}} \times (p + v - e - f - l - c - d - o - r) \times rei_{EU}) + (GHG_{\text{X}} \times i \times rei_{X}) \tag{2}$$

where $GHG_{\text{EU}}$ and $GHG_{\text{X}}$ are the GHG emissions per kg of food (kg $CO_2$eq) produced in Europe and the continent of production of imports, respectively, and $rei_{EU}$ and $rei_{X}$ are the relative emission intensities in Europe and the continent of production of imports, respectively.

To estimate per-capita GHG emissions, total GHG emissions ($EM_{\text{tot}}$) were divided by the UK population in a given year. GHG emissions were then summed by broad food groups ('Assigned category', Table 1 and Table S1). To aid interpretability, "cow, mutton and goat", which includes lamb, is referred to as ruminant meat. The difference between GHG emissions of food production between continents was accounted for, but it was not possible to account for emissions of transport involved in importing foods due to insufficient data. GHG emissions of food production include emissions involved in converting land to agriculture, but do not include opportunity costs (GHG sequestration potential through ecosystem restoration that is not realised when land is being used for agriculture [Hayek et al., 2021]).

It was assumed that exports were domestically produced (or at least produced within Europe, see equation (2)). While this is a simplification, for most food groups this assumption was appropriate due to high proportion of domestic production relative to imports. For food groups where export quantities were high relative to production quantities however, this could lead to errors in emissions estimates. For example, if foods were imported to the UK, processed, then exported as a new product, and if emission intensity of the continent of production of imports (where the main continent of production of imports was not Europe) greatly exceeded that of production within Europe, it was possible that negative GHG emissions were estimated. Data on the continent of production of exports were not available, so it was not possible resolve this problem. 6% of estimated values across food types and years (176 out of 2768 estimated values) had negative emissions values. This was primarily composed of food types with low food supply and high net export rates so was not expected to introduce substantial errors into GHG emissions of UK food supply. To test this, the error introduced by omitting food groups with negative emissions was estimated. For food types and years where negative values of food supply were estimated, the emission intensity of the continent of maximum imports was multiplied by UK food supply for that food type. It was estimated that the mean error of omitting foods with negative emission estimates (summed across food groups) was 0.1% of total UK food supply emissions. As such, for each year and food type where negative emissions were estimated, emissions were set to 0 as genuine food supply emissions of less than 0 were not possible.

### 3.1.5. *The relative contribution of supply-side change, demand-side change and trade*

To examine the contribution of changes in supply-side change the contribution of changes in emission intensity to reductions in per-capita GHG emissions was calculated. Food supply quantity and composition and trade were first held constant at 1986 levels, and per-capita GHG emissions were calculated for 1986 and 2017.

Demand-side changes were measured by assessing the impact of changes in the quantity and composition of food supply. This was an appropriate means of measuring demand-side changes as all food supplied is consumed or wasted so demand-side changes including dietary change and changes in waste are described by changes in food supply. Emission intensity and trade were held constant at 1986 levels, and per-capita GHG emissions were calculated for 1986 and 2017. The difference between 2017 and 1986 per-capita GHG emissions under these conditions was $d'$ (t/capita/year) and indicates the contribution of both dietary change and changes in retail and household waste to changing GHG emissions of UK food supply.

This was repeated for trade ($t'$, t/capita/year), by holding emission intensity and food supply constant at 1986 levels.

The relative contributions of supply-side changes (emission intensity) ($I$), demand-side changes ($D$) and trade ($T$) to reductions in per-capita GHG emissions ($E$) from UK food supply were then calculated as shown in equations (3)–(5) respectively:

$$I = E \times \left(\frac{i'}{d' + i' + t'}\right) \tag{3}$$

where $I$ is the relative contribution of changes in supply-side change (%) to reduction in per-capita GHG emissions and $E$ is the reduction in per-capita GHG emissions from UK food supply between 1986 and 2017 (%, relative to 1986).

$$D = E \times \left(\frac{d'}{d' + i' + t'}\right) \tag{4}$$

where $D$ is the relative contribution of demand-side change (%) to reduction in per-capita GHG emissions and $E$ is the reduction in per-capita GHG emissions from UK food supply between 1986 and 2017 (%, relative to 1986).

$$T = E \times \left(\frac{t'}{d' + i' + t'}\right) \tag{5}$$

where $T$ is the relative contribution of changes in trade patterns (%) to reduction in per-capita GHG emissions and $E$ is the reduction in per-capita GHG emissions from UK food supply between 1986 and 2017 (%, relative to 1986).

Mixed effects models were used to provide a complementary method of assessing the relative contribution of supply and demand-side changes to GHG emissions. As there were multiple emissions estimates for each year (one for each food type), a mixed effects model was used with food supply quantity, relative emission intensity and proportion of imports as fixed explanatory variables, and food type as a random explanatory variable. If absolute emission intensity of food products was used (emissions per kilogram of product) it would not be possible to separate the contribution of emission intensity to variance in emissions estimates between food types, and between years. To overcome this, relative emission intensity (emission intensity divided by emission intensity in measurement year, see Section 3.1.3) was used instead. The proportion of imports could not be calculated when food supply was 0, so these data points were discarded. Where food supply was less than import quantity, the proportion of imports for this year and food type was set to 1 (it was assumed that all food supply came from imports). Data were centred and scaled to allow comparison of effect sizes between explanatory variables. Diagnostic plots revealed non-normal distribution of residuals. Due to right-skewed distribution of emission estimates (dependant variable) and food supply quantity (fixed explanatory variable) both variables were log10-transformed, following which diagnostic plots indicated no violation of assumptions. The significance of fixed effects was estimated using the *mixed* function in library *afex* (Singmann et al., 2023).

Data on total emissions from enteric fermentation, manure (including emissions from manure management, manure left on pasture and manure applied to soils), synthetic fertilisers and crop residues (including emissions from burning crop residues) for UK food produce were downloaded from FAOSTAT (FAO, 2021b) from the '*Emissions Shares*' tab for 1986 and 2017. This was used to compare the contribution of different emission sources to changes in food supply emissions. As emission intensity data were not disaggregated by emission source, and data on emission totals were produced from a production perspective (per head of livestock) rather than a consumption perspective (per kg of food) it was not possible to integrate changes disaggregated emission intensity by emission source in the analysis of food supply emissions between 1986 and 2017. As such the values here describe total emissions from each emission source, occurring as a result of both changes in food supply (dietary change and waste) and changes in production efficiency.

## 3.2. *Comparison to the Planetary Health Diet*

Data on food supply (in g/capita/day) for 1986 and 2017 were aggregated according to categories used by the PHD (see Tables 1 and 2). This means that beef, lamb and pork were grouped together despite the lower GHG emissions of pork relative to beef and lamb. Grouping beef, lamb and pork was appropriate as they have similar nutritional qualities and grouping pork and poultry (closer GHG emissions to pork than beef and lamb) would not allow comparison to the PHD without the use of limiting assumptions. Food supply measures the food available to buy, not the food consumed. As such, values of food supply include food that is wasted in the home and in retail. This is appropriate when calculating the environmental impact of food supply because even if food is wasted the environmental impact is still realised. Despite this, when comparing to dietary guidelines of food consumption, the overestimation of calorific intake can be problematic. By normalising the calorific intake of the PHD (2500 calories) to that of food supply (3212 kcal/capita/day in 1986 and 3393 kcal/capita/day in 2017, produced by FAO, 2021b), this problem can be overcome. PHD recommendations were normalised as shown in equation (6).

$$PHD_n = \frac{S_{\text{cap}\times}\, cal_{FAO}}{cal_{PHD}} \tag{6}$$

**Table 2**
Food types used when comparing the UK diet to the Planetary Health Diet.

| Planetary Health Diet category | Planetary Health Diet Guideline (g/capita/day, assuming a 2500 calorie diet) | Foods included (FAO Commodity Balances) |
|---|---|---|
| **Beef, lamb and pork** | 14 | Bovine Meat + Mutton and Goat + Pigmeat |
| **Tubers and starchy vegetables** | 50 | Cassava and products + Potatoes and products + Roots, other + Yams |
| **Eggs** | 13 | Eggs |
| **Chicken and other poultry** | 29 | Poultry Meat |
| **Dairy** | 250 | Butter, Ghee + Milk- Excluding Butter + Cream |
| **Fish** | 28 | Demersal Fish + Fish, Body Oil + Freshwater Fish + Marine fish, Other + Pelagic Fish |
| **Vegetables** | 300 | Olives (including preserved) + Onions + Peas + Tomatoes and products + Vegetables, Other |
| **Fruit** | 200 | Apples and products + Bananas + Citrus, Other + Dates + Fruits, Other + Grapefruit and products + Grapes and products (excl. wine) + Oranges, Mandarins + Pineapples and products + Plantains |
| **Legumes** | 75 | Beans + Peas + Pulses, Other and products + Soyabeans |
| **Whole grains** | 232 | Barley and products + Cereals, Other + Maize and products + Oats + Rice and products + Rye and products + Sorghum and products + Wheat and products |
| **Nuts** | 50 | Groundnut (Shelled Eq) + Nuts and products |

*Eq = equivalent (indicating primary values have been converted by FAO to mass of the specified food type).

where $PHD_n$ (g/capita/day) is normalised per-capita PHD intake, $S_{cap}$ (g/capita/day) is per-capita supply, $cal_{FAO}$ (kcal/capita/day) is the number of calories supplied per day according to FAO and $cal_{PHD}$ is the number of calories in the PHD reference diet (2500 kcal/capita/day). Supply was expressed as a percentage of normalised PHD recommendations for each food category. This method is a simplification since overestimation by food balance sheets may vary by food type.

To calculate the GHG emissions that could be abated by aligning with the PHD, the proportion of over or underconsumption relative to PHD guidelines was calculated for each food type in 2017 (Table 2, equation (7)). The total per-capita GHG emissions in 2017 was then multiplied by this proportion. This method assumed that emission intensity and trade patterns do not change, and the composition of consumption within each food type remains constant.

$$EM_{\mathrm{PHD}} = \frac{PHD_n \times GHG_{2017}}{S_{\mathrm{cap}}} \tag{7}$$

where $EM_{\mathrm{PHD}}$ is the per-capita GHG emissions (t/capita/y) of the PHD aligned diet, $PHD_n$ is normalised recommended intake according to the PHD (g/capita/day, equation (6)), $GHG_{2017}$ is the per-capita GHG emissions of UK food supply in 2017 (t/capita/y) and $S_{\mathrm{cap}}$ is per-capita food supply for 2017 in the UK.

Per-capita GHG emissions of the PHD-aligned diet ($GHG_{\mathrm{PHD}}$) were compared to per-capita GHG emissions of food supply in 2017 ($GHG_{2017}$). This method was used to assess how GHG emissions of UK food supply would change if the composition of the UK diet aligned with the PHD. Calorific intake was controlled for and therefore potential changes in the total quantity of food consumed were not considered. Consumption of food groups not specified in the PHD (such as sugar) were assumed to remain the same. By using change in composition of food supply to examine the impact of dietary change, this assumed the quantity of food wasted is proportional to the quantity consumed.

## 4. Results

### *4.1. Greenhouse gas emissions of UK food supply between 1986 and 2017*

Between 1986 and 2017 total GHG emissions from UK food supply fell by 20%, from 259 $MtCO_2eq$ to 208 $MtCO_2eq$ (Fig. 2). Over the same interval per-capita GHG emissions fell by 32%, from 4.6 $tCO_2eq$/capita to 3.1 $tCO_2eq$/capita. Supply-side changes, demand-side changes and changes in trade patterns all contributed to these declines. Changes in emissions intensity were the greatest contributor, resulting in a 21% reduction in per-capita emissions. Demand-side changes resulted in a 10% decrease in per-capita emissions, predominantly due to falling demand for ruminant meat, dairy and animal fats and offals. Changes in trade patterns resulted in a 2% decrease in per-capita emissions. The impact of changing trade patterns was dependent on food type, and food produced closer to the UK did not always have lower GHG emissions.

Per capita emissions from ruminant meat ("cow, mutton and goat" on Fig. 2) fell by 35% between 1986 and 2017 (Table 3). While changes in demand contributed most to emissions reductions from ruminant meat supply (16%), changes in emission intensity and trade patterns made a substantial contribution (9% and 10% respectively). Reduction in ruminant meat supply was associated with a decrease in domestic production (24.0 kg per-capita in 1986 to 18.0 kg per-capita in 2017) and a small decrease in net imports (8.4 kg per-capita in 1986 to 7.7 kg per-capita in 2017). Changing trade patterns resulted in a reduction in emissions as imports of bovine meat were increasingly sourced from Europe (89% of imports in 2017 compared to 67% in 1986) and less so from Latin America (down from 25% of imports in 1986 to 8% in 2017). Mutton (including lamb) and goat meat were increasingly sourced from Europe (less so from Oceania) which marginally increased per-capita emissions as emission intensity was higher than in Oceania (in 2005 43.0 $kgCO_2/kg$ in Europe compared to 37.9 $kgCO_2/kg$ in Oceania).

Falling emissions from dairy made the greatest contribution to reduction in total emissions relative to other food groups. Per capita emissions from dairy supply fell by 50% between 1986 and 2017. This was predominantly due to a reduction in emission intensity, which resulted in a 35% decline in per-capita emissions from dairy between 1986 and 2017. Falling demand resulted in an 18% reduction in per-capita emissions from dairy. Falling demand was associated with a decrease in domestic production (298 kg per capita in 1986 compared to 232 kg per capita in 2017) and change in the net flow of trade. In 1986, the UK was a net exporter of dairy products (net export of 43.2 kg per capita) whereas in 2017 imports exceeded exports (31.5 kg per capita). As such, a greater proportion of dairy supply came from imports in 2017 compared to 1986, with these imports increasingly sourced from Europe (99% of imports in 2017 compared with 70% in 1986) rather than Oceania (29% of imports in 1986 compared to <1% of imports in 2017). As emission intensity of dairy production was lower in Oceania than Europe (for 2005, 1.6 $kgCO_2/kg$ in Oceania vs 2.2 $kgCO_2/kg$ in Europe), changing trade patterns increased per-capita emissions from dairy supply by 3% over the time period studied.

Per-capita emissions from pork and poultry showed little change between 1986 and 2017. Changes in demand differed between pork and poultry with a reduction in demand for pork (and decrease in domestic production) and substantial increase in demand for poultry (with an increase in domestic production and net imports).

Animal fats, offals and other meats make up a small component of overall per-capita emissions (7% in 1986 and 3% in 2017) but showed a large percentage reduction (68%) in per-capita emissions between 1986 and 2017 primarily due to decrease in demand. While falling demand was associated with a moderate increase in domestic production (4.2 kg per capita in 1986 compared to 6.1 kg per capita in 2017), the UK

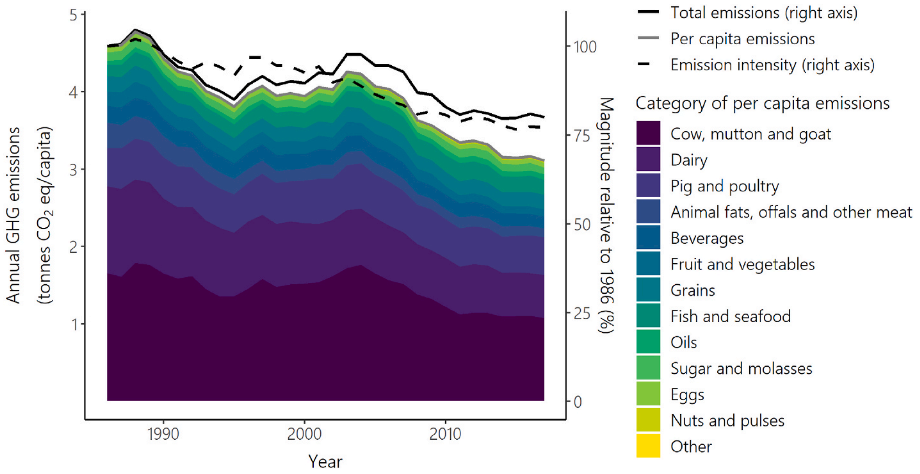


**Fig. 2.** Per capita greenhouse gas emissions (left axis, tonnes $CO_2$eq/capita) by food category between 1986 and 2017, also showing changes in total emissions and emission intensity (right axis, % relative to 1986). As the impact of trade is dependent on the composition of the UK diet, a separate line for trade is not shown.

**Table 3**
Change in per-capita greenhouse gas emissions between 1986 and 2017 (%) showing relative contribution of changes in emission intensity, trade patterns and demand.

| Food group | Emission intensity (%) | Trade patterns (%) | Demand (%) | Total (%) |
|---|---|---|---|---|
| **Ruminant meat (cow, mutton and goat)** | −9 | −10 | −16 | −35 |
| **Dairy** | −35 | 3 | −18 | −50 |
| **Pork and poultry** | 1 | > −1 | −1 | > −1 |
| **Animal fats, offals and other meats** | −27 | −1 | −41 | −68 |
| **Beverages** | −21[a] | 17 | −24 | −28 |
| **Fruit and vegetables** | −21[a] | −15 | −14[c] | −50 |
| **Grains** | 3 | −1 | −4 | −2 |
| **Fish and seafood**[b] | n.a. | n.a. | 28 | 28 |
| **Oils** | −4[a] | 9 | 20 | 25 |
| **Sugar** | 23[a] | −57 | 20 | −14 |
| **Eggs** | −11 | > −1 | −5 | −16 |
| **Nuts and pulses** | 45[a] | 148 | 61 | 254 |
| **Other** | −7 | 77 | 87 | 158 |

[a] For plant-based foods (other than grains) emission intensity data was coarse, so the relative contribution of emission intensity is an approximation based on changes in emission intensity of grains.

[b] We did not estimate the impact of trade patterns and emission intensity on emissions from fish and seafood due to lack of source data.

[c] Changes in emissions from transport due to changing quantities of imports were not accounted for. For most food groups the proportion of emissions attributable to transport is low (<10% [Poore and Nemecek, 2018]) but for some food groups, such fruit and vegetables, transport is responsible for a higher proportion of total emissions, accounting for a mean of 25.5% of emissions (Poore and Nemecek, 2018). Assuming 73% of fruit and vegetable transport emissions are due to overseas imports (Garnett, 2006), it is estimated that emissions of transport from overseas imports of fruit and vegetables were responsible for 34.66kgCO$_2$eq/capita in 1986. If emissions were proportional to the quantity of imports this would result in 62.39kgCO$_2$eq/capita in 2017. This would give a total per-capita decline in emissions from fruit and vegetables of 26% rather than 50% as shown in Table 1, and the increase in emissions due to trade would have a higher relative contribution. The impact of trade is particularly pronounced for fruit and vegetables as the quantity of fruit and vegetable imports more than doubled over the time period. A simplifying assumption here is that the quantity of fruit and vegetables transported by ships and air remained the same between 1986 and 2017. The values have been left as calculated according to the method described in Section 3.1.5 to provide consistency across food groups.

became a net exporter of animal fats, offals and other meats between 1986 and 2017. The quantity lost during processing and packaging (albeit a small proportion of production) increased from 0.3 kg per-capita in 1986 to 0.6 kg per-capita in 2017. The quantity of animal fats, offals and other meats put to non-food uses decreased from 3.6 kg per capita in 1986 to 0.8 kg per capita in 2017. As calculated, fruit and vegetable per-capita emissions decreased by 50% over the same time period, although accounting for increasing emissions from overseas transport of fruit and vegetable imports gave a more modest decrease of 26% (see footnote c, Table 3). Per-capita emissions from grain supply showed little change between 1986 and 2017. Increased demand for fish and seafood resulted in increased emissions from this food group (net emissions increase of 28%). Emissions from nuts and pulses increased substantially between 1986 and 2017 (by 254%) due to increase in emission intensity, rise in demand and changing trade patterns. Per-capita emissions from eggs decreased by 16%, from sugar decreased by 14%, from oils increased by 25% and from beverages decreased by 28%.

As expected, food supply quantity (demand-side, $p < 0.001$), relative emission intensity (supply-side, $p < 0.05$), and proportion of imports (trade, $p < 0.01$) were all important for explaining variation in food supply emissions. The effect size was greatest for food supply quantity. This was not expected as supply-side changes (changes in emission intensity) were responsible for a greater change in GHG emissions than demand-side changes (changes in food supply quantities) when calculated according to equations (3) and (4). A possible explanation for this is that relative changes in emission intensity were more important for food types with high emissions. This is supported by the fact that when a mixed effects model was applied only to foods with the high emissions (top ten total emissions over the time period), the effect size of relative emission intensity was closer to (albeit still smaller than) that attributable to food supply quantity. Variation between food types explained a large proportion of variance in GHG emissions estimates (96% of model variance).

The emission intensity of UK produce declined for all food types between 1986 and 2017, except for bovine meat. Emission intensity of UK produced bovine meat increased by 3% over the time period, in contrast to the 46% reduction in emission intensity of bovine meat production in Europe. Across all food types, emission intensity of UK produce declined by a mean of 16%.

Declines in emissions from enteric fermentation, manure (including emissions from manure management, manure left on pasture and manure applied to soils), synthetic fertilisers and crop residues (including emissions from burning crop residues) all contributed to the falling emissions of UK food produce. Declines in emissions from enteric

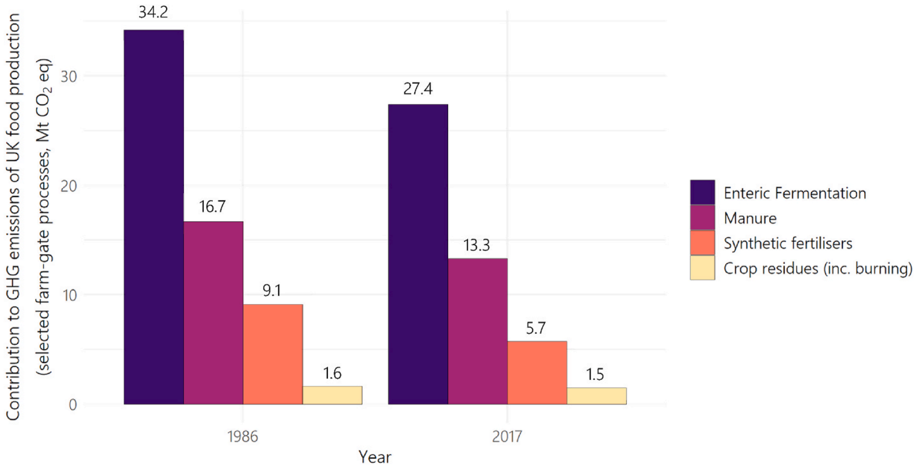


**Fig. 3.** Contribution of selected farm-gate processes (including enteric fermentation, manure, synthetic fertilisers and crop residues) to greenhouse gas emissions (Mt $CO_2$eq/capita) of UK food production in 1986 and 2017.

fermentation were the greatest, falling by 6.8Mt$CO_2$eq (−20%) between 1986 and 2017 (Fig. 3), followed by emissions from manure (3.4Mt$CO_2$eq reduction, −20%) and synthetic fertilisers (3.4Mt$CO_2$eq reduction, −37%). As these are total emissions and not emissions per kg of product (emission intensity) these declines include supply- and demand-side changes.

### 4.2. Comparison to the Planetary Health Diet

Relative to the PHD, the average person in the UK greatly over-consumes beef, lamb and pork, tubers and starchy vegetables and dairy products, yet under-consumes vegetables, legumes and nuts (Fig. 4). While the UK moved closer towards the PHD over the period 1986–2017, further population wide dietary change is needed to reduce the environmental impact of the UK food system. It was estimated that if the UK followed the PHD, UK per-capita emissions could be reduced by a further 42% compared to 2017. There was a reduction in emissions by 49% from food groups covered by the PHD (consumption of other food groups was assumed to remain stable).

Reduction in consumption of beef, lamb and pork contributed most to the difference in GHG emissions between 2017 UK consumption and the PHD (Fig. 5). It was estimated that if the UK food supply contained the same proportion of beef, lamb and pork as recommended by the PHD (19g when normalised to a calorie supply of 3393 kcal/capita/day and assuming the same relative contribution of beef, lamb and pork as in 2017 [39%, 9% and 52% respectively]), this change alone would result in an annual reduction of 1.11 tonnes $CO_2$eq/capita of GHG emissions, 36% of 2017 UK per-capita emissions. Reduction in consumption of dairy, and chicken and other poultry were the next greatest contributors to the lower GHG emissions of the PHD, offering 7% and 5% reduction in per-capita emissions respectively. Increased consumption of those foods that were under-consumed in the 2017 UK diet relative to the PHD would only increase per-capita GHG emissions by 10%, far less than the total abated (60%) by reducing overconsumption of other categories of food.

## 5. Discussion

Total GHG emissions from UK food supply declined by 20% between 1986 and 2017 and per-capita emissions declined by 32%. Supply-side changes (falling emission intensity) made the greatest contribution to this decrease, with a smaller but notable reduction resulting from demand-side changes. Changing trade patterns resulted in a small decrease in per-capita emissions. Comparing between food groups revealed the significance of emissions reductions from ruminant meat and dairy, and the complex relationship between trade patterns and

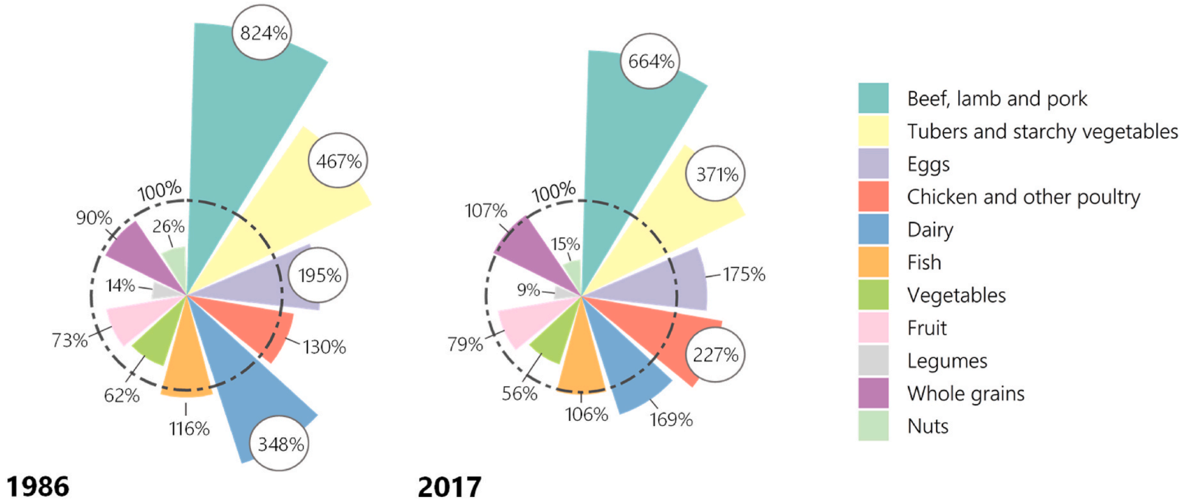


**Fig. 4.** Comparison of the composition of the UK diet to the PHD (EAT-Lancet Commission, 2019) in 1986 and 2017, where 100% (dashed line) indicates that daily consumption in the UK is equal to the PHD. Normalised to a 2500 calorie diet.

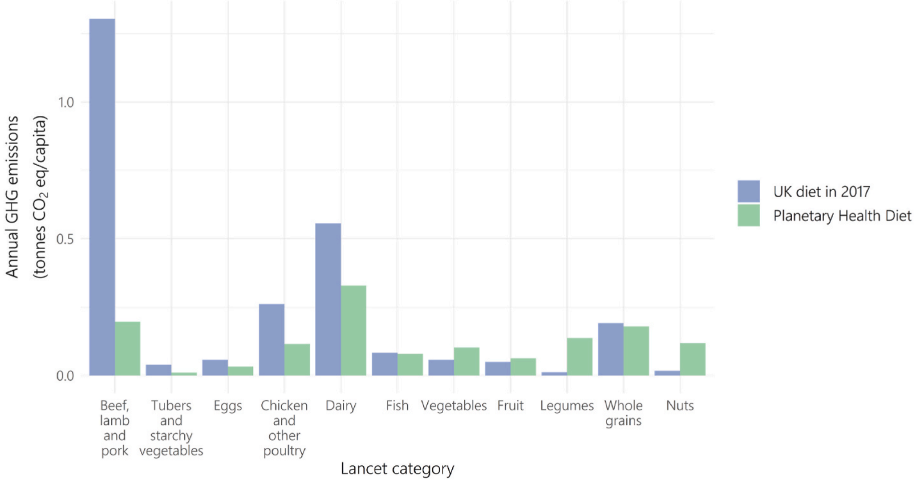


**Fig. 5.** Annual per-capita GHG emissions (tonnes/$CO_2$eq/capita) of the UK diet in 2017 and the Planetary Health Diet (PHD), shown by food groups used to define the PHD (Lancet category).

GHG emissions from food supply. Comparison to the PHD highlights the very substantial opportunity for further GHG emissions reductions from dietary change, with reduction in beef, lamb and pork supply contributing greatest to this decline. Inclusion of changing trade patterns highlighted the increasing overseas impact of UK food consumption (de Ruiter et al., 2016).

This study was subject to several limitations, the most notable being the lack of in-depth data on temporal changes in emission intensity. Without data on emission shares disaggregated by product (and expressed per unit of product as bought), it was not possible to integrate temporal changes in pre-and post-production and land use change emissions. As such temporal changes in farm-gate emissions were assumed to be representative of changes in emissions pre- and post-production and changes in emissions from land use change. Farm gate, pre- and post-production and land use changes constitute 60.5%, 33.7%, and 5.8% of food supply emissions (from seed to the shop shelf) in Europe respectively (FAO, 2021b). While emissions from land use change and pre- and post-production declined in the UK over the time period studied, these declines were smaller than reductions in emissions from farm gate processes. As such the relative contribution supply-side measures may have been overestimated in this study. Findings presented here therefore provide an indication of how changing emission intensity has affected emissions of UK food supply but increasing availability of temporal emission intensity data by food product, country and emission source should be prioritised for future research.

Emissions from transport were not accounted for when considering GHG emissions from food imports. Transport constitutes a small proportion of food supply emissions (the sum of emissions from retail, processing and packaging sums to 1–9% of total food supply emissions [Poore and Nemecek, 2018]), and the impact this will have on estimation of trends in GHG emissions vary between food types and changing country of import. For fruit and vegetables however, the impact is greater due to low emissions of production and high proportion of imports. Accounting for emissions from transport for fruit and vegetables resulted in emissions reductions of 26% rather than 50% (without import transport emission changes). As GHG emissions from transport were low proportion of total GHG emissions for all other food groups (Poore and Nemecek, 2018), and the increase in imports was particularly high in fruit and vegetables, it is not expected that this will greatly influence the findings presented for other food groups. The opportunity cost of food production was not included, so these results did not include the carbon sequestration potential of restoration of unused agricultural land arising from changing food supply. If opportunity costs were considered, the reduction in GHG emissions when aligning with the PHD would likely be greater due to the high land requirement of meat production (Hayek et al., 2021), which was overconsumed in the UK in 2017 relative to the PHD. When calculating the mitigation potential of adoption of the PHD, emission intensity of food production was assumed to remain constant. If, in future, supply-side changes (such as increase in use of renewable energy) result in a reduction in emission intensity heterogeneously across food groups, this will alter mitigation potential of dietary change.

Despite these boundaries and limitations, comparison with the literature suggests the emissions estimates presented here are relatively robust. Total GHG emissions in 2005 was 147Mt$CO_2$ after subtracting roughly 40% of total emissions resulting from land use change [Audsley et al., 2009]). This is comparable to that of Audsley et al. (2009) and Defra (2009) who estimated total UK food GHG emissions to be 152Mt$CO_2$ and 159Mt$CO_2$ in 2005 respectively. Our finding that total food supply emissions reduced by 20% between 1986 and 2017 in the UK is comparable to that calculated by the Department for Business, Energy and Industrial Strategy (2017), who found a 16% decrease in GHG emissions from the food system between 1990 and 2016.

Supply-side changes (falling emission intensity) made the greatest contribution to reduction in GHG emissions from UK food supply between 1986 and 2017 (21%). Despite this, food emissions have decarbonised at less than half the rate of declines in the wider economy (Dimbleby, 2021). Further opportunities for reduction in emission intensity are available through technology improvements and emission efficient farming practices (Garvey et al., 2021), but reductions in emission intensity may slow in future (Bennetzen et al., 2016). Demand-side changes made a notable contribution to falling emissions from UK food supply (10%). Reduction in demand of ruminant meat and dairy was particularly influential. The contribution of demand-side changes to historical trends in GHG emissions, reveals the potential importance of demand-side changes for future food GHG emissions mitigation. Our finding that rising proportion of imports of fruit and vegetables was associated with higher GHG emissions reveals synergies in tackling concerns over food security and GHG emissions, as reducing imports of fruit and vegetables would also decrease dependence on production in climate vulnerable countries (Scheelbeek et al., 2020b).

There was no straightforward relationship between trade and GHG emissions from food supply. Whether domestic or international food production had lower emissions was dependent on the food group and continent of production – so that falling domestic supply of dairy, for example, was associated with a decrease in GHG emissions, yet falling domestic supply of fruit and vegetables resulted in an increase in GHG emissions. For some food groups, such as bovine meat, changing the provenance of imports to locations closer to the UK helped lower emissions, while for others, such as mutton and goat, sourcing imports from nearer the UK resulted in an increase in GHG emissions. These findings add to recent evidence that the relationship between food trade and GHG emissions of food supply is non-trivial (Edwards-Jones, 2010). As such, messages which encourage consumers to eat locally to lower food supply emissions may be an oversimplification of the relationship between trade and environmental impact.

Comparison of the UK diet in 2017 to the PHD demonstrates that a much greater reduction in GHG emissions from UK food supply is possible through dietary change. Garvey et al. (2021) found that the UK could reduce the absolute annual territorial GHG emissions of its food system by 22–44% through dietary change, and Jarmul et al. (2020) found a mean reduction of 25.8% in GHG emissions when compiling results of switching to sustainable diets globally. Here it was found that UK per-capita emissions of food supply could be reduced by 42%. This is relatively high compared to other estimates, likely due to the ambitious targets set by the PHD. Switching from an "average" diet to the PHD would involve radical changes to consumption patterns, but could maintain or improve dietary health as well as contribute greatly to cutting food-related GHG emissions (EAT-Lancet Commission, 2019).

### 5.1. *Theoretical implications*

Both supply- and demand-side changes contributed to historical reductions in GHG emissions of UK food supply. Rather than a fixed and unchanging diet, the last thirty years have seen consumption patterns change flexibly alongside changing socioeconomic and agricultural conditions. This is promising for the application of demand-side measures for future GHG emissions reductions.

The findings presented here shed light on the relationship between trade and food sustainability. There was no simple relationship between trade patterns and GHG emissions, and with production emissions far exceeding transport emissions for most food types (Poore and Nemecek, 2018), this analysis suggests that eating local is not always more sustainable (Weber and Matthews, 2008).

### 5.2. *Implications for practice*

Sustainable, healthy and flexible reference diets, such as the PHD, provide an opportunity to deliver considerable emissions reductions. Integrating sustainability criteria into dietary guidelines is one way to enhance uptake of sustainable reference diets (Garvey et al., 2022). Canada, Switzerland, Sweden, Qatar, Norway, Brazil and Germany have already included sustainability criteria into national dietary guidelines (Mouthful, 2020). If sustainability criteria are effectively integrated into dietary guidelines in other countries, and these guidelines are followed, this could deliver progress towards reductions in food emissions required to meet net zero by 2050 (Forbes et al., 2021).

The emissions embedded in food production were highly variable between continents. As such, distributors, producers, and processors aiming to make sustainable choices need to consider GHG emissions in the continent of production of their food products and ingredients. Citizens need to be aware that just because food may be advertised as local, this does not mean the GHG emissions involved in supplying that food are necessarily lower. Because of the complexity of the relationship between trade and GHG emissions of food supply, efforts to make information on GHG emissions easier to access are key to informing such decisions. One way of providing consumers with this information is through carbon labelling (Taufique et al., 2022).

### 5.3. *Implications for policy*

The importance of both supply- and demand-side measures in contributing to UK food supply emissions highlights the importance of a diversified approach to emissions reductions (Audsley et al., 2009). Supply-side emissions reductions may slow in the future, while demand-side changes still hold great potential for food emissions mitigation. The potential impact of adopting the PHD reveals the utility of a healthy, sustainable, and flexible reference diet for delivering win-win solutions for human health and sustainability. Citizens could help make this change, but it is not their responsibility alone (Marteau et al., 2021). Policy mechanisms which improve the accessibility, affordability and desirability of healthy and sustainable food are essential to enable the food system to transition towards a sustainable future.

## 6. Conclusions

In conclusion both supply- and demand-side changes have contributed to falling emissions of UK food supply. Per-capita emissions declined by 32% (1.5 $tCO_2eq$/capita) between 1986 and 2017 and a further 42% reduction (1.3 $tCO_2eq$/capita) in emissions could be achieved if the composition of the UK diet was aligned with the Planetary Health Diet. Sustainable, healthy and flexible diets such as the Planetary Health Diet could become an increasingly important mitigation strategy as supply-side emissions reductions slow. Ensuring the accessibility and affordability of healthy and sustainable food is key to enabling equitable dietary change. Alongside this, due to the complexity of factors which affect the GHG emissions of food production, improving availability of information on environmental impact is important to allow informed consumer choice. Overall, the findings presented here highlight the importance of a diversified approach to food supply emissions reductions, with demand-side measures posing great opportunities for future mitigation strategies.

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## CRediT authorship contribution statement

**Kerry Stewart:** Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Software, Validation, Visualization, Writing – original draft, preparation, Writing – review & editing. **Andrew Balmford:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Visualization, Writing – review & editing. **Pauline Scheelbeek:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Visualization, Writing – review & editing. **Anya Doherty:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Emma E. Garnett:** Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Software, Supervision, Visualization, Writing – review & editing.

## Declaration of competing interest

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

## Data availability

Data used in this analysis is freely available from cited sources.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.jclepro.2023.137273.

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