INTERFACE

rsif.royalsocietypublishing.org

Research

**Cite this article:** de Ruiter H, Macdiarmid JI, Matthews RB, Kastner T, Smith P. 2016 Global cropland and greenhouse gas impacts of UK food supply are increasingly located overseas. *J. R. Soc. Interface* **13**: 20151001. http://dx.doi.org/10.1098/rsif.2015.1001

Received: 18 November 2015
Accepted: 4 December 2015

**Subject Areas:**
environmental science

**Keywords:**
global environmental impacts, food supply, land use, international trade, self-sufficiency

**Author for correspondence:**
Henri de Ruiter
e-mail: henri.deruiter@hutton.ac.uk

Electronic supplementary material is available at http://dx.doi.org/10.1098/rsif.2015.1001 or via http://rsif.royalsocietypublishing.org.

THE ROYAL SOCIETY PUBLISHING

# Global cropland and greenhouse gas impacts of UK food supply are increasingly located overseas

Henri de Ruiter[1,2], Jennie I. Macdiarmid[3], Robin B. Matthews[1], Thomas Kastner[4] and Pete Smith[2]

[1]Information and Computing Sciences Group, The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK
[2]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen AB24 3UU, UK
[3]Public Health Nutrition Research Group, Rowett Institute of Nutrition and Health, University of Aberdeen, Aberdeen AB25 2ZD, UK
[4]Institute of Social Ecology Vienna, Alpen-Adria Universität Klagenfurt, Wien, Graz, Schottenfeldgasse 29, Vienna 1070 Austria

HR, 0000-0001-7352-9317; RBM, 0000-0003-4685-6210; TK, 0000-0002-8155-136X; PS, 0000-0002-3784-1124

Producing sufficient, healthy food for a growing world population amid a changing climate is a major challenge for the twenty-first century. Agricultural trade could help alleviate this challenge by using comparative productivity advantages between countries. However, agricultural trade has implications for national food security and could displace environmental impacts from developed to developing countries. This study illustrates the global effects resulting from the agricultural trade of a single country, by analysing the global cropland and greenhouse gas impacts of the UK's food and feed supply. The global cropland footprint associated with the UK food and feed supply increased by 2022 kha (+23%) from 1986 to 2009. Greenhouse gas emissions (GHGE) associated with fertilizer and manure application, and rice cultivation remained relatively constant at 7.9 Mt $CO_2$e between 1987 and 2008. Including GHGE from land-use change, however, leads to an increase from 19.1 in 1987 to 21.9 Mt $CO_2$e in 2008. The UK is currently importing over 50% of its food and feed, whereas 70% and 64% of the associated cropland and GHGE impacts, respectively, are located abroad. These results imply that the UK is increasingly reliant on external resources and that the environmental impact of its food supply is increasingly displaced overseas.

## 1. Background

Demand for food will be a major driver of global environmental change in the coming decades [1], through its impact on, among others, land use and greenhouse gas emissions (GHGE). Globally, agriculture accounts for about 40% of total land area [2], and the agriculture and forestry sector is responsible for just under a quarter of global anthropogenic GHGE [3]. In a globalized world, the demand for food is increasingly met by resources outside a country's own territory [4], and currently, almost a quarter of all food produced for human consumption is traded internationally [5]. As a result, the world has moved towards an increasing reliance on food trade in order to feed its population and this has important implications for food security [6,7]. The increasing dependency on trade reflects the use of natural resources, because more than 20% of the global cropland area is presently used for exports [8]. In general, international trade flows from high-yield to low-yield regions, suggesting that it is contributing to a more efficient global food system [8]. However, concerns have been raised over the role of trade in the displacement of environmental impacts by shifting the burden from developed to developing countries [9]. This displacement has been studied in the context of $CO_2$ emissions, showing that consumption-based accounts of developed countries' emissions are increasing, whereas production-based accounts are stabilizing or even decreasing [10]. This difference between production-based and consumption-based accounting has important consequences for effective climate policy and hence the choice of metrics has key implications. Most global consumption-based accounts on $CO_2$ emissions are estimated from multi-region input–output analyses (MRIOs) and consider $CO_2$ emissions of the economy as a whole. More recently, the effects of international trade on other environmental indicators such as land use have also been included in consumption-based MRIO accounts [11]; however, there is an ongoing debate as to whether these MRIO models are suited to examine land-use displacements, or whether biophysical models are better suited [12–14]. A possible reason for these at times divergent accounts of land-use displacements is the differences in metrics underlying the accounting. A recent study showed that the choice of monetary, nutritional or resource metrics could greatly affect conclusions about whether a country is, for instance, a net importer or net exporter of croplands [15].

While global studies give a good indication of the magnitude of the environmental consequences of trade, analysing the displacement effects of trade for one specific country provides information about the specifics of the global effects of local consumption [16]. Therefore, the aim of this study was to analyse the global environmental impacts over time associated with the national food supply of a developed country. The UK was used as a case study for this analysis because it represents a developed, high-income country which is heavily dependent on food imports.

The present analysis considers the environmental impacts related to crops used for food and feed, as it has been shown that dietary change could achieve a larger reduction in carbon emissions than supply-side mitigation measures [17] with the potential for co-benefits for public health [18]. Synergies between health, emissions and land-use reduction will be highly relevant from a policy perspective [18].

The complexities of current food supply chains and lack of available data make it very difficult, in some cases impossible, to trace individual food items back to their place of production, especially, because, most bilateral trade data report only the last country in the supply chain [19,20]. Therefore, for this study, a recently developed biophysical dataset was used, which allows flows of crop and livestock products to be traced and consistently allocated to cropland areas in over 200 countries [8]. The use of this dataset overcomes the problem of bilateral trade data, and thereby gives a better indication of the allocation of crop and livestock products to their cropland area. In this study, this dataset was used to calculate the domestic and overseas cropland footprint of the UK food and feed supply for the period 1986–2009. The calculated cropland footprint was subsequently used to analyse the associated GHGE, comprising synthetic fertilizer, manure application to soils, rice cultivation and emissions arising from land-use change (LUC). This study, therefore, highlights the effects of trade on the self-sufficiency of the UK, and the displacement of cropland and GHGE impacts to other countries.

## 2. Methods

This study uses data from a recently developed dataset [8], based upon FAOSTAT data [21], for calculating total trade volumes for the UK and their associated cropland footprint. A brief overview of this methodology is given here, but for more details, see the original study [8]. The accounting system assumes that the domestic production of the UK is either used for domestic use or for exports (production perspective). The domestic consumption of the UK is either supplied by domestic production or by imports (consumption perspective). The resulting values represent the total crop (food and feed) supply at the national level, including processed products such as bread and pasta, and hence differ from actual food intake or household food availability owing to, for instance, waste along the supply chain. By assuming that imports and domestic production of a given crop contribute to the country's domestic consumption and exports in proportional shares, consistent production and consumption perspectives can be established for 157 crops on a global scale. One hundred and ten of these crops are included in this study; crops that do not ultimately contribute to the human diet were excluded, e.g. cottonseed and tobacco (see electronic supplementary material, table S1 for details of the crops). At the time of the analysis, no exports were reported for Cote d'Ivoire, a major supplier of cocoa beans and coffee for the UK, for the period 1986–1996. Therefore, a linear trend was assumed for the supply of cocoa beans and coffee to the UK, using the period 1997–2009 as a base, and extrapolated to the period 1986–1996.

Not all crops contribute 100% to human food or animal feed; most notably oil palm fruit. Therefore, although the analysis is based on food and feed crops, not all of the environmental impact may be related to food. Experimental statistics show that approximately 0.4–1.7% of total UK arable land was used for biofuel production in the period 2008–2012 [22]. No data are available for earlier years; it is therefore assumed that crops for fuels played a negligible role over the study period.

All processed products, e.g. soya bean oil, were converted and allocated to their primary commodity, as described by Kastner *et al.* [8], preventing double counting for crop products. Only cropland is considered in this study, grasslands were not part of the analysis. Animal products and feed use are converted to obtain the amount of 'crops in animal products' and hence the associated cropland requirements can be calculated. Cropland requirements were calculated using country-specific yields for the respective years. Thus, the consumption perspective shows the shares of 255 countries in the apparent consumption of 110 crops in the UK, and the production perspective shows in which of the 255 countries the UK food production is consumed.

Individual crops were grouped into FAO categories (see electronic supplementary material, table S1 for an overview), and all countries were grouped into world regions according to the classification used by [8]. Countries included in the EU15+ region were kept the same over the entire period, e.g. the enlargement of the EU did not affect our composition of the regions, to keep results for the EU15+ consistent for the studied period (see electronic supplementary material, table S2). Energy and protein supply were calculated using FAO nutritional value data [23]. As this study analyses crop supply resulting from food and feed, calculated energy and protein availabilities represent energy and protein that are available before they are converted to livestock products. As such, the amount of protein and energy is higher than the actual availability of protein and energy to the general population. All data presented in figures and tables are 3-year averages around the respective years.

### 2.1. Calculation of fertilizer application

Crop-specific synthetic nitrogen fertilizer rates for Europe and the UK were obtained from Fertilizers Europe [24], and the British Survey of Fertilizer Practice 2010 [25]. Crop-specific nitrogen application rates for the rest of the world were calculated using crop-specific nitrogen fertilizer consumption data from the international fertilizer industry (IFA) for the year 2010/2011, the most recent version with the largest number of crops and countries available [26]. Data from Fertilizers Europe and the British Survey of Fertilizer Practice were obtained for the year 2010 to match IFA figures. IFA consumption figures (for 13 major crop categories in the 27 main nitrogen fertilizer consuming countries) were converted to crop-specific application rates by dividing the total nitrogen consumption figures for each crop by the harvested area for the corresponding crop [21]. To calculate the changes in fertilizer application rates over the time period, annual total fertilizer consumption in a region was obtained [21], and the % change in total fertilizer consumption was divided by the % change in 'arable land and permanent crops' in the corresponding year. For example, total fertilizer consumption in South America in the year 2000 was about 50% of the total fertilizer consumption in the year 2010, and total 'arable land and permanent crops' area in 2000 was 84% of that in the year 2010. Combining these figures leads to a nitrogen application rate in 2000 that represents 60% of the nitrogen application rate in 2010. It was then assumed that the calculated change in fertilizer application rates over the study period was uniform across all the different crop categories, i.e. all crop categories from South America in 2000 received 60% of their 2010 nitrogen application rate, and uniform across types of land, because FAO figures do not distinguish between grasslands and croplands fertilizer consumption. A recent study suggests that in most countries the share of total nitrogen fertilizer applied to grasslands increased over the period 1986–2009, whereas this share in most European countries decreased from the year 2000 onwards [27]. In general, the share of nitrogen fertilizer applied to grasslands is much lower than the share for croplands. Thus, our assumption of uniform changes for grasslands and croplands may slightly overestimate nitrogen fertilizer use in the later stages of the studied period, and slightly underestimate nitrogen fertilizer use from the year 2000 onwards for European countries. For stimulant crops, nitrogen application rates were obtained for specific countries from the FAO database 'fertilizer use by crop' ($n = 23$ for coffee; $n = 13$ for tea and $n = 12$ for cocoa) [28]. If the respective country was not available in this dataset, then nitrogen rates of a neighbouring country were used. Fertilizer figures for stimulant crops were only available for different years and ranged therefore from 1988 to 2003. In contrast with the fertilizer application rates of other crops, no changes in fertilizer application were assumed for stimulant crops, as the data were only available for different years and as stimulant crops receive a relatively low amount of fertilizers. For cocoa production in Ghana and Ivory Coast, the two main exporting countries to the UK, no nitrogen use was assumed, as the FAO reports for Ghana that fertilizer use on cocoa was negligible [29]. For countries that were part of the 'rest of the world' category of the IFA, total crop-specific fertilizer consumption was divided by the harvested area of all crop areas in the remaining countries.

## 2.2. Calculation of manure application

Nitrogen is also applied on soils by manure, though the nitrogen input by manure is much smaller on a global scale than synthetic fertilizer nitrogen input [30]. Manure application rates were calculated using a two-step approach. First, total annual manure nitrogen input to soils was obtained and divided by total harvested area in the corresponding year (both obtained from [21]) to give the average manure nitrogen input per hectare for a given country in a given year (equation (2.1))

$$M\,\text{appl}_i(t) = \frac{M\,\text{cons}_i(t)}{\text{area}_i(t)}, \tag{2.1}$$

where $M$ appl$_i(t)$ is the average application rate (kg N ha$^{-1}$) for manure nitrogen in country $i$ for the year $t$; $M$ cons$_i(t)$ is the total manure nitrogen input (kg N) according to the FAO in country $i$ for the year $t$ and area$_i$ $(t)$ is the total harvested area (ha) according to the FAO in country $i$ in the year $t$. To account for the different nitrogen requirements of different crops, it was assumed that manure nitrogen is spread in the same proportions as synthetic fertilizers (equation (2.2)). That is, if vegetables require twice as much nitrogen from synthetic fertilizer as cereals, then we assume that vegetables receive twice as much manure nitrogen as well.

$$M\,\text{crop}_{i,j}(t) = \frac{F\,\text{crop}_{i,j}(t)}{F\,\text{appl}_i(t)} \times M\,\text{appl}_i(t), \tag{2.2}$$

where $M$ crop$_{i,j}(t)$ is the calculated manure nitrogen application rate (kg N ha$^{-1}$) in country $i$ for crop $j$ in the year $t$; $F$ crop$_{i,j}(t)$ is the crop-specific nitrogen application rate (kg N ha$^{-1}$) for synthetic fertilizer in country $i$ for crop $j$ for the year $t$; $F$ appl$_i(t)$ is the average application rate (kg N ha$^{-1}$) for synthetic nitrogen fertilizer in country $i$ and year $t$ and $M$ appl$_i$ $(t)$ is the average application rate (kg N ha$^{-1}$) for manure nitrogen in country $i$ in the year $t$ (equation (2.1)). The crop-specific fertilizer nitrogen application rates ($F$ crop$_{i,j}$) were obtained from the previous synthetic fertilizer input calculations. The average fertilizer application rates ($F$ appl$_i$) were obtained by dividing total fertilizer consumption in a country [26] by total harvested area of all crops in the corresponding country, or by using average fertilizer application rates from Fertilizers Europe [24] and the British Survey of Fertilizer Practice 2010 [25]. Because it was assumed that changes in fertilizer consumption over the study period were uniform across the crop categories, the factor $F$ crop$_{i,j}$/F appl$_i$ was kept constant over time. This two-step approach gave an average crop-specific manure nitrogen application rate for each country in each year of the study period. In some regions, fertilization levels are limited by legislation. Using the approach described here, in only three countries do calculated fertilization rates exceed recommended rates (Netherlands, Ireland and Belgium). While the current method may overestimate manure application rates for these three countries, this is unlikely to have a large impact on our overall findings.

## 2.3. Greenhouse gas emission calculation related to fertilizer and manure application, and rice cultivation

Crop-specific nitrogen application rates for synthetic fertilizer and manure were multiplied by the cropland area associated with the UK supply of the respective crop to give the total nitrogen input associated with each crop. Both direct GHGE from fertilizer and manure application, as well as indirect emissions owing to leaching and volatization, were calculated using the IPCC tier 1 factors [31]. A global warming potential of 298 (100-year time horizon) was used to convert $N_2O$ to $CO_2$-equivalents ($CO_2$e) [32].

To account for methane emissions during rice cultivation, implied emission factors for rice cultivation [21] were multiplied by the calculated rice cultivation area associated with the UK crop supply. Methane emissions were converted to $CO_2$e by using a factor of 34 (100-year time horizon) [32].

## 2.4. Greenhouse gas emission associated with land-use change

To calculate LUC emissions, a 'top-down' approach was used, as described in [33], based on the consideration that all agricultural commodity markets are global in nature and highly interconnected. From this perspective, all global LUC emissions should be allocated to agricultural land itself, not only to recently cleared land, resulting in a calculated average emission of LUC for every hectare in agricultural use [34]. Values obtained from [34] are used here, which are 5.8 Gt $CO_2$e per year for all LUC emissions, and a total global agricultural area of 4.9 Gha, resulting in average

**Table 1.** Trends in volume, calories and protein imported into the UK from each world region as percentages of total food and feed supply. Values are 3-year means around the respective year.

| | tonnes (% of total) | | kcal (% of total) | | protein (% of total) | |
|---|---|---|---|---|---|---|
| | 1987 | 2008 | 1987 | 2008 | 1987 | 2008 |
| domestic | 64 | 52 | 62 | 51 | 57 | 46 |
| North America | 5 | 3 | 8 | 3 | 17 | 5 |
| Central America | 1 | 1 | 1 | 1 | 0 | 0 |
| South America | 3 | 10 | 5 | 12 | 8 | 26 |
| EU 15+ | 15 | 19 | 14 | 19 | 12 | 16 |
| FSU and other Europe | 1 | 3 | 1 | 4 | 1 | 4 |
| Sub-Saharan Africa | 2 | 2 | 3 | 2 | 1 | 1 |
| Northern Africa and Western Asia | 2 | 2 | 1 | 1 | 0 | 0 |
| Eastern Asia | 1 | 1 | 1 | 1 | 1 | 1 |
| Southern Asia | 1 | 1 | 1 | 1 | 1 | 1 |
| Southeast Asia | 3 | 5 | 3 | 4 | 1 | 1 |
| Oceania | 1 | 1 | 2 | 1 | 1 | 0 |

LUC emissions of 1.18 tonne of $CO_2e$ for every hectare of agricultural land. To compensate for a limitation of this approach, namely that all crops carry the same burden per hectare, we use normalization factors for the 25 major global crops based on their relative expansion rates in the period 1990–2010 [35]. For example, soya beans, where cropland areas have expanded rapidly, receive a normalization factor of 1.36, compared with, for instance, a factor of 0.78 for barley, for which cropland areas have decreased. The same LUC emission factor is used throughout the studied period.

## 3. Results

The dependence of the UK on international trade to meet its food needs has increased substantially over the period 1986–2009. Total annual crop-related food and feed supply in the UK increased from 56 in 1987 to 71 Mt yr$^{-1}$ in 2008. Part of this increased demand can be explained by the increase in population, which grew from 57 million people in 1987 to 62 million people in 2008. However, the *per capita* supply still grew from 985 to 1148 kg cap$^{-1}$ yr$^{-1}$. In 2008, 48% of the total UK food and feed was imported from abroad, compared with 36% in 1987 (table 1). The same picture emerges for energy (calories) and protein supply: in 2008, trade imports accounted for about 50% of total supply, whereas this percentage was about 40% in 1987 (table 1). Total energy availability for feed and food combined increased from 5522 in 1987 to 6892 kcal cap$^{-1}$ d$^{-1}$ in 2008; protein availability for feed and food combined increased from 192 to 259 g cap$^{-1}$ d$^{-1}$.

The main trading region in terms of volume was Europe, responsible for about one-fifth of the total crop supply. The share from North America in the total supply has decreased over time, whereas South America's share has increased substantially since 1986. After domestic food production, European agricultural production is most important for the supply of energy to the UK, with almost a fifth of all calories coming from the EU in 2008. Most of the protein is imported from South America owing to the large imports of high-protein

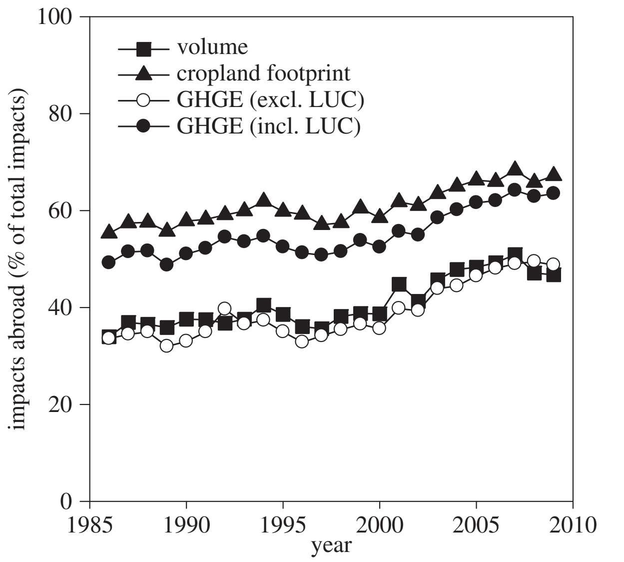


**Figure 1.** Overseas impact of UK food and feed supply on cropland use and carbon emissions as percentage of total impact.

oil crops such as sunflower seed and soya beans, which are mainly used for animal feed.

The increasing dependence on international trade is reflected in the rising environmental impact abroad, albeit at a slower pace than total trade volume. The total cropland footprint of the UK food and feed supply increased from 8900 in 1987 to 10 922 kha in 2008, or from 1562 to 1774 m$^2$ cap$^{-1}$ yr$^{-1}$ in 2008 (+14%). In 1987, about 57% of this cropland footprint associated with UK crop supply was located abroad and this increased to about 67% in 2008 (figure 1). The largest increase in cropland footprint is observed in South America (+1437 kha) followed by the Former Soviet Union (+791 kha). Figure 2 shows the change in percentage points of the world regions' contributions to the total UK cropland footprint from 1986 to 2009. It shows that the importance of North America has decreased over time (from 14% to 5%), whereas the importance of particularly South America has

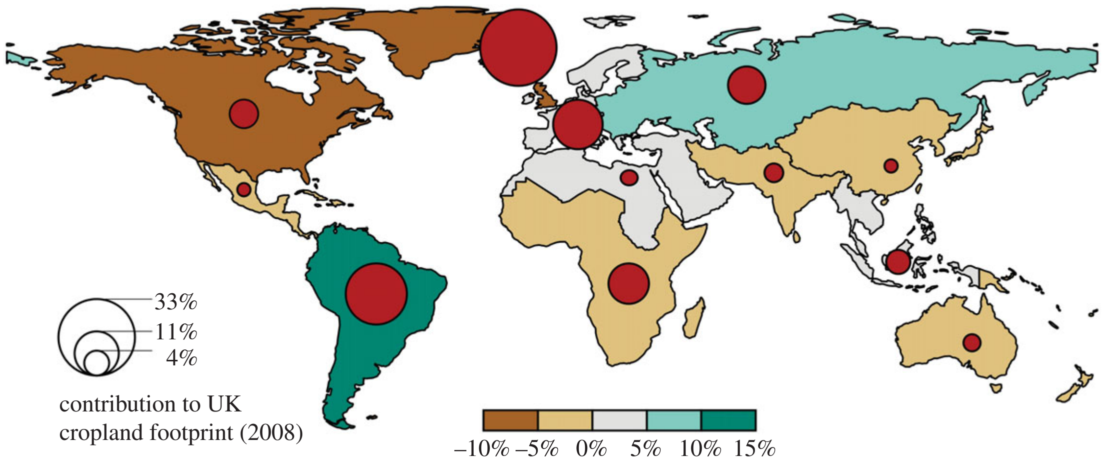


**Figure 2.** Relative contribution of the different world regions to the UK's cropland footprint. Colours show the change in percentage points of the world regions' contributions to the total UK cropland footprint from 1986 to 2009. Proportional circles show the relative contribution of the world regions to the UK's cropland footprint in 2008 (3-year mean).

**Table 2.** Impacts of the main crop categories. Values are 3-year means around the respective year. Note that the impacts are the sum of domestic impacts and impacts abroad.

| | tonnes (kton) | | land area (kha) | | GHGE (excl. LUC) (kton $CO_2$e) | | GHGE (incl. LUC) (kton $CO_2$e) | |
|---|---|---|---|---|---|---|---|---|
| | 1987 | 2008 | 1987 | 2008 | 1987 | 2008 | 1987 | 2008 |
| cereals | 20 775 | 26 925 | 4141 | 4384 | 5681 | 5309 | 10 214 | 10 203 |
| roots and tubers | 8156 | 7453 | 265 | 193 | 278 | 173 | 589 | 400 |
| sugar crops | 10 859 | 9838 | 662 | 474 | 514 | 355 | 1256 | 887 |
| pulses | 689 | 1120 | 272 | 572 | 100 | 156 | 501 | 1000 |
| nuts | 49 | 69 | 38 | 42 | 9 | 9 | 65 | 70 |
| oil crops | 5247 | 11 161 | 1991 | 3350 | 669 | 1131 | 3641 | 6048 |
| vegetables | 5779 | 7362 | 247 | 304 | 271 | 287 | 608 | 693 |
| fruits | 4074 | 6072 | 382 | 437 | 157 | 219 | 634 | 772 |
| spices | 23 | 56 | 24 | 44 | 13 | 30 | 49 | 96 |
| stimulants | 474 | 643 | 877 | 1119 | 252 | 211 | 1546 | 1861 |
| total | 56 124 | 70 699 | 8900 | 10 922 | 7943 | 7878 | 19 101 | 21 856 |

increased (from 10% to 21%). Crops responsible for the decrease in cropland area in North America are mainly cereals (see electronic supplementary material, figures S1–S10 for crop category-specific maps), whereas the increase for South America is mainly caused by oil crops. Figure 2 also shows the relative contribution of the different world regions to the total UK footprint in 2008. The share of domestic cropland in the total cropland footprint is largest (33%), followed by the share of South America (21%) and EU15+ (14%). Individual countries responsible for the largest share in the UK's cropland footprint are Argentina and Brazil, both contributing about 9% to the total UK cropland footprint.

## 3.1. Contribution of different crops to cropland footprint

In absolute terms, oil crops, cereals and stimulant crops (i.e. cocoa, coffee and tea) are responsible for the largest increase in the cropland footprint, whereas the contribution of sugar crops and roots and tubers decreased (table 2). The cropland footprint associated with oil crops increased by 1359 kha (+68%), whereas that associated with stimulant crops increased by 242 kha (+28%), mainly owing to an increase in cocoa bean imports. Cropland for oil crops increased both domestically (+238 kha) and abroad (+1121 kha). Cropland area for domestically supplied cereals decreased (−183 kha), whereas total cropland area for cereals abroad increased by 426 kha. Crops particularly important for human health, such as fruit and vegetables, are also increasingly sourced from abroad, with an increase from 429 in 1987 to 608 kha in 2008, whereas the domestic cropland footprint of the UK fruit and vegetables supply has steadily decreased over time (from 201 kha in 1987 to 133 kha in 2008). The main countries abroad for supplying the UK's fruit and vegetables are Spain, China and Italy

Soya bean was the commodity responsible for the largest cropland footprint abroad with 1502 kha (20% of total imported cropland; and 14% of the total land footprint), followed by cocoa beans with 872 kha (12% and 8%, respectively) and

**Table 3.** Crops responsible for the largest land appropriation abroad. Values are 3-year means around the respective years.

| | embodied cropland (kha) (2008) | percentage of total imports (2008) | embodied cropland (kha) (1987) | percentage of total imports (1987) |
|---|---|---|---|---|
| soya beans | 1502 | 20 | 1040 | 21 |
| cocoa beans | 872 | 12 | 552 | 11 |
| wheat | 787 | 10 | 688 | 14 |
| sunflower seed | 524 | 7 | 286 | 6 |
| maize | 388 | 5 | 352 | 7 |
| beans, dry | 367 | 5 | 90 | 2 |
| rapeseed | 345 | 5 | 124 | 2 |
| barley | 284 | 4 | 164 | 3 |
| sugar, refined | 275 | 4 | 306 | 6 |
| oil palm fruit | 201 | 3 | 105 | 2 |
| total top 10 | 5545 | 75 | | |

wheat with 787 kha (10% and 7%, respectively; table 3). Ten crops imported into the UK were responsible for about 75% of the total cropland footprint abroad. The largest absolute increase for individual crops in the total cropland footprint of the UK supply is observed for soya beans and rapeseed (+461 and +460 kha, respectively).

## 3.2. Net displacement of land

Figure 3 shows that the net imported cropland footprint (i.e. domestic cropland plus cropland abroad minus cropland used for exports, or *consumption perspective* minus *production perspective* in figure 3) has increased substantially from 1987 to 2008. In 1987, the UK imported a net cropland area of 3475 kha and this increased to 6468 kha in 2008. Total domestic agricultural cropland area decreased (−216 kha), and the share of domestic cropland used for exports also decreased from 29% in 1987 to 19% in 2008. The main exports-receiving region was the EU15+ in both 1987 and 2008, receiving about 12% of all exported cropland in 1987 and about 11% in 2008. The UK was a net exporter of cropland to the Former Soviet Union and Northern Africa and Western Asia in 1987; however, in 2008, the UK was a net importer of cropland from all regions.

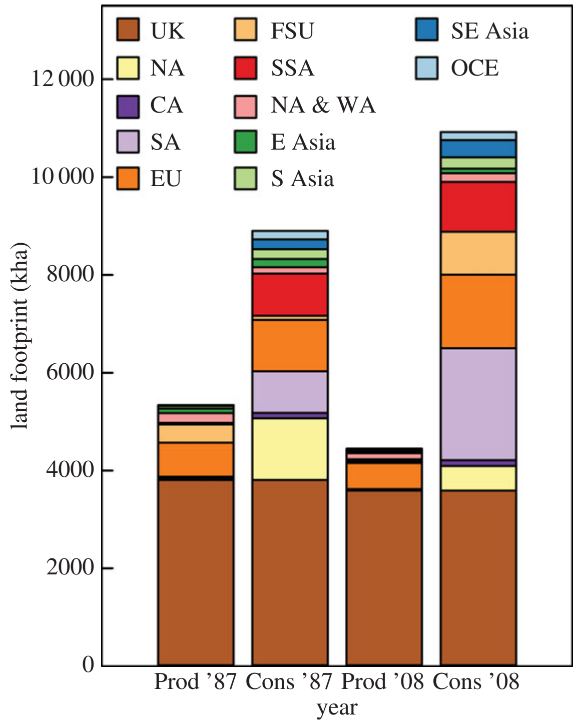


**Figure 3.** Cropland footprint for the UK calculated from a production and consumption perspective for 1987 (left) and 2008 (right). The values are 3-year means around the respective years. NA, North America; CA, Central America and Caribbean; SA, South America; EU, EU15+; FSU, Former Soviet Union; SSA, Sub-Saharan Africa, NA and WA, North Africa and Western Asia; E Asia, East Asia; S Asia, Southern Asia; SE Asia, Southeast Asia; OCE, Oceania.

## 3.3. Greenhouse gas emissions associated with UK crop supply

Total GHGE, excluding emissions from LUC, remained relatively constant over the studied period. This, however, masks an underlying trend where the share of synthetic fertilizer in the GHGE declined from 76% to 68%, whereas the share of rice increased from 10% to 15%. The decline in GHGE from fertilizer application was mainly caused by decreasing fertilizer application rates in the two regions responsible for the largest production of the UK crop supply (UK and EU15+).

When GHGE from LUC are included, a clear increase in total GHGE is observed, from 19.1 in 1987 to 21.9 Mt $CO_2$e in 2008, primarily because of a larger cropland footprint. LUC emissions represent the largest contributor to total GHGE, with a share of 64% in 2008, with fertilizer application contributing a further 24%, manure application 6% and rice cultivation 5%. As a consequence, GHGE are increasingly located abroad. While in 1987 about 50% of the emissions were emitted overseas, this had increased to 62% in 2008 (figure 1), with most emitted in South America (18%) and the EU (15%).

## 3.4. Contribution of different crops to greenhouse gas emissions

GHGE of most crop categories increased over time, mostly as a consequence of the larger area associated with each crop

**Table 4.** Land and GHGE intensities of the UK food and feed supply, total UK production, total imports and exports, and imports and exports to the EU.

| | land (ha kg$^{-1}$) | | GHGE (kg $CO_2$e kg$^{-1}$) | |
|---|---|---|---|---|
| | 1987 | 2008 | 1987 | 2008 |
| total UK supply | 0.16 | 0.15 | 0.34 | 0.31 |
| total UK production | 0.12 | 0.11 | 0.34 | 0.26 |
| total imports | 0.25 | 0.22 | 0.48 | 0.41 |
| total exports | 0.18 | 0.15 | 0.50 | 0.38 |
| total EU imports | 0.13 | 0.11 | 0.31 | 0.26 |
| total EU exports | 0.18 | 0.15 | 0.51 | 0.39 |

(table 2). GHGE of roots and tubers and sugar crops decreased over time, as a result of a smaller cropland area and lower fertilizer use. GHGE associated with cereals remained constant, despite a larger cropland area associated with cereals, which can be explained by a lower fertilizer use in the UK and EU15+, the main regions supplying cereals. Wheat was the largest source associated with UK food and feed supply and was responsible for 25% of all emissions (not shown). Soya beans, barley and rapeseed were the other major sources of total GHGE. Wheat was the major source of GHGE overseas, representing 18% of all GHGE abroad, followed by soya beans (17%) and cocoa beans (7%).

### 3.5. Land and greenhouse gas emissions intensities

Table 4 shows the differences in land and GHGE intensities per kilogram of crop supplied (in ha kg$^{-1}$ and $CO_2$e kg$^{-1}$, respectively). It shows that, on average, land and GHGE intensities have decreased over time, with yield improvements being the driving factor. It also shows that the intensity of the average UK crop supply is higher than the intensities of domestically produced crops (total UK production, i.e. it includes domestically supplied crops and crops for exports). Imports to the UK have a higher intensity than UK exports, suggesting a displacement of environmental impact. However, when analysing UK–EU trade, the opposite is observed: UK imports from the EU have lower intensities than UK exports to the EU. The primary reason for this is not necessarily a difference in productivity, but, because, the UK imports higher yielding crops from the EU, most notably vegetables.

## 4. Discussion

This study shows that the UK is increasingly reliant on international trade to satisfy its food and feed demand which is accompanied by a shift in the environmental impact beyond its own territory. This is consistent with previous studies showing the impact on other environmental indicators, for example, 75% of the water footprint of the UK lies overseas [36] and approximately 40% the UK's GHGE (associated with all consumption activities) are emitted abroad [37].

This analysis for the UK indicates that domestic cropland for food and feed production has decreased, as has the amount of cropland used for exports, suggesting that the increase in cropland imports reflects a real displacement of cropland use to other countries rather than a generic increase in trade volume (figure 3). This is different from, for instance, an analysis for Finland showing both increasing imports and exports of embodied land, resulting in increasing net displacement of land for food for the period 1991–2007 [38].

Nevertheless, it is consistent with the wider picture of the EU as a net importer of agricultural products and displacer of environmental impact to other world regions, despite the fact that European yields are among the highest in the world [39]. This is different from the global trend, where, on average, agricultural trade flows are from high-yielding regions to low-yielding regions [8]. Intra-European trade, however, tends to be consistent with the global picture, where high footprint countries tend to be net exporters of environmental impact [39]. This might be explained by the trade-off between scale of consumption and efficiency of production [39]. European countries not only have an efficient agricultural system, but also a high level of consumption. Because imports have a high resource intensity compared with exports, most European countries become net displacers of environmental impact. However, within Europe, consumption differences are much smaller and resource intensities are more a result of structural and natural differences. As a result, countries with a lot of resources, such as France and Spain in the case of land, specialize and become net exporters of land within the EU [39]. The present analysis confirms this observation, with the UK importing land and GHGE intensive commodities from the rest of the world, both as a result of lower yields in other regions (e.g. for cereals) and because of the type of crops (e.g. soya beans). On the other hand, the UK imports on average low resource-intensive products from the EU15+, mainly as a result of a high import of vegetables, which have a higher average EU15+ yield than domestically produced vegetables. As such, UK–EU15+ trade suggests a beneficial role of trade for agricultural efficiency, but trade with the rest of the world displaces environmental effect (table 4).

The total cropland footprint for UK food supply (10 922 kha or 1774 m$^2$ cap$^{-1}$ yr$^{-1}$) is similar to a recent estimate of the German cropland footprint, excluding German cropland for roughages (14 450 kha or 1762 m$^2$ cap$^{-1}$ yr$^{-1}$) [40]. Germany's land footprint abroad is dominated by soya beans and cocoa beans, broadly in line with the current UK results. Oil crops are largely used for feed in the livestock sector, and dietary change is often suggested as a means to decrease the environmental impact of food consumption and/or dependence on food imports as the production of animal products is inherently inefficient. If Europe reduced its livestock production by 50%, then the use of imported soya bean meal would drop by 75% and the EU would become a large net exporter of basic food commodities [41]. In addition, changes in consumption of animal products are also relevant from a public health perspective, as a lower consumption of animal products could have co-benefits for public health [42,43]. An important consideration here is what would be grown on freed up cropland as a result of lower animal consumption, and what people would eat instead of animal products. Ideally, the available cropland would be used to grow crops that would benefit human health and people would shift towards food items with lower environmental impacts that are also healthy. Theoretically, the UK could achieve full self-sufficiency; however, this would imply drastic shifts in consumption patterns [44], away from stimulant crops, animal products and many types of fruit and vegetables, which may not be feasible or acceptable.

While attention tends to be focused on animal products, the present analysis suggests that the supply of stimulant crops is increasingly responsible for a large land appropriation abroad (see also [40,45]), and associated GHGE from LUC. While stimulants are not a necessary part of a nutritionally balanced diet, they are culturally embedded in the consumption patterns of many countries. This highlights the multiple and diverse effects of international trade; on the one hand, it displaces environmental impact, on the other hand, it enables economic development in developing countries through international trade.

This study suggests that the total GHGE associated with the UK food supply have remained relatively constant over the studied period. However, this overall trend masks some underlying trends, where fertilizer use on UK and EU croplands has declined, causing GHGE from fertilizer use to fall, whereas GHGE related to rice imports have increased. When emissions from LUC are included, an increase in GHGE is seen, with LUC GHGE being the largest contributor to total GHGE. This highlights the importance of including LUC emissions in assessing GHG impact of food consumption. In addition, there may be a trade-off between products that have low associated GHGE with fertilizer use and other sources of GHGE, but by requiring more land, they are responsible for a larger share in LUC emissions. This highlights not only the importance of including LUC GHGE, but also the choice of method for dealing with GHGE from LUC.

The UK's full supply chain emissions from all consumption activities were 1106 Mt $CO_2e$ [37]. Agriculture and food production accounted for about 120 Mt $CO_2e$ [46]. Another study, using life-cycle analysis for a wide range of foods and processes, estimates the total direct emissions of UK food consumption at 152 Mt $CO_2e$ for the year 2005, with a further 101 Mt $CO_2e$ attributable to LUC related to the UK food consumption [33]. The estimated emissions of 7.9 Mt $CO_2e$ (excluding LUC) and 21.9 Mt $CO_2e$ (including LUC), in this study, are lower because this study does not consider other sources of GHGE such as enteric fermentation (responsible for 16 Mt $CO_2e$ in [33]) or LUC and fertilizer use attributable to grazing areas (LUC emissions related to grassland area were responsible for more than 50% of total LUC emissions in [33]).

It is not easy to relate FAOSTAT figures to actual household or individual food consumption [47]. The food supply data used in this study suggest, for instance, that the total amount of available vegetables *per capita* doubled over the study period. In contrast, household statistics suggest that consumption of vegetables decreased slightly over the study period [48]. This could have several reasons, for instance more vegetables could be wasted along the supply chain or used for animal feed. Therefore, one should be cautious in using food supply statistics to assess dietary changes or quality.

### 4.1. Limitations of the study

Currently, there is not an established method of relating emissions from LUC to food, and a wide range of methods have been suggested [49,50]. By using a global average LUC emission factor for each crop in this study, a comparatively heavy burden is assigned to established croplands, whereas LUC emissions from recently cleared croplands are underestimated. This has been partly counteracted by normalizing emissions based on expansion rates of crops. Still, this approach does not consider differences in crop expansion rates between regions, or whether a particular crop has primarily expanded into forest or into other types of land. In addition, using one LUC emission factor based on recent estimates for global LUC emissions and agricultural area, for the entire period might underestimate LUC emissions in earlier decades as deforestation rates have slowed over the past decades [51]. The current method of dealing with LUC emissions does not provide obvious mitigation options, and will only favour efficiency and crop yields as strategies for reducing LUC emissions [49]. However, because the objective of this study is to highlight historical changes in the UK's cropland footprint and associated GHGE, rather than suggesting mitigation options, it is an appropriate method for estimating LUC impacts. In addition, other methods of dealing with LUC emissions need more spatially aggregated data and information on the type of land that has been converted, something that is not readily available for every country in the world.

This study considers GHGE from fertilizer application, manure application, rice cultivation and LUC. It does not consider emissions from other sources, such as emissions from enteric fermentation or LUC attributable to grazing area, which are both major sources of GHGE [30,51]. Extending the present analysis by including grasslands and emissions arising from enteric fermentation will give a more complete picture of the total environmental impact of the UK food supply. In addition, data on national crop-specific fertilizer application rates are only available for a limited number of crops and years, and large variations in application rates exist on a subnational scale. This study used country-level nitrogen application rates, in order to be consistent with national trade data. Finally, emissions from LUC could potentially be addressed in a more spatially aggregated way, taking into account the types of land and the biomes that have been converted to agricultural land.

## 5. Conclusion

To conclude, total environmental impact is ultimately driven by consumption, yet governments mostly focus on low impact per unit of production within national boundaries and give less consideration to addressing consumption volumes and patterns [20]. The effects of trade on the displacement of environmental impacts are mostly analysed in a global context for the sum of all consumption activities. Although such studies provide us valuable insights, analysing specific countries and specific activities such as food consumption will be needed for policymaking as most decisions are still made at a national level.

Authors' contributions. H.R., J.M., R.B.M. and P.S. initiated and designed the study. T.K. provided the initial data for the study and commented on draft versions of the paper. H.R. carried out most of the analysis, and wrote the draft and final version of the manuscript. J.M., R.B.M. and P.S. supervised the study and commented on draft versions of the manuscript. All authors gave final approval for publication.

Competing interests. We declare we have no competing interests.

Funding. This work was supported by a University of Aberdeen Environment and Food Security Theme/the James Hutton Institute PhD studentship, and contributes to the Scottish Food Security Alliance-Crops and the Belmont Forum supported DEVIL project

(NERC fund UK contribution: NE/M021327/1). J.M. and R.B.M. acknowledge funding from the Rural and Environment Science and Analytical Services, Scottish Government. T.K. acknowledges funding from the European Research Council Grant ERC-263522 (LUISE).

## References

1. Tilman D *et al.* 2001 Forecasting agriculturally driven global environmental change. *Science* **292**, 281–284. (doi:10.1126/science.1057544)
2. Foley JA *et al.* 2011 Solutions for a cultivated planet. *Nature* **478**, 337–342. (doi:10.1038/nature10452)
3. Smith P *et al.* 2014 Agriculture, forestry and other land use (AFOLU). In *Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. O Edenhofer *et al.*) Cambridge, UK: Cambridge University Press.
4. Lambin EF, Meyfroidt P. 2011 Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl Acad. Sci. USA* **108**, 3465–3472. (doi:10.1073/pnas.1100480108)
5. D'Odorico P, Carr JA, Laio F, Ridolfi L, Vandoni S. 2014 Feeding humanity through global food trade. *Earth's Future* **2**, 458–469. (doi:10.1002/2014EF000250)
6. Fader M, Gerten D, Krause M, Lucht W, Cramer W. 2013 Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environ. Res. Lett.* **8**, 014046. (doi:10.1088/1748-9326/8/1/014046)
7. Porkka M, Kummu M, Siebert S, Varis O. 2013 From food insufficiency towards trade dependency: a historical analysis of global food availability. *PLoS ONE* **8**, e82714. (doi:10.1371/journal.pone.0082714)
8. Kastner T, Erb KH, Haberl H. 2014 Rapid growth in agricultural trade: effects on global area efficiency and the role of management. *Environ. Res. Lett.* **9**, 034015. (doi:10.1088/1748-9326/9/3/034015)
9. Meyfroidt P, Lambin EF, Erb K, Hertel TW. 2013 Globalization of land use: distant drivers of land change and geographic displacement of land use. *Curr. Opin. Environ. Sustainability* **5**, 438–444. (doi:10.1016/j.cosust.2013.04.003)
10. Peters GP, Minx JC, Weber CL, Edenhofer O. 2011 Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl Acad. Sci. USA* **108**, 8903–8908. (doi:10.1073/pnas.1006388108)
11. Weinzettel J, Hertwich EG, Peters GP, Steen-Olsen K, Galli A. 2013 Affluence drives the global displacement of land use. *Glob. Environ. Change* **23**, 433–438. (doi:10.1016/j.gloenvcha.2012.12.010)
12. Henders S, Ostwald M. 2014 Accounting methods for international land-related leakage and distant deforestation drivers. *Ecol. Econ*. **99**, 21–28. (doi:10.1016/j.ecolecon.2014.01.005)
13. Kastner T, Schaffartzik A, Eisenmenger N, Erb K, Haberl H, Krausmann F. 2014 Cropland area embodied in international trade: contradictory results from different approaches. *Ecol. Econ*. **104**, 140–144. (doi:10.1016/j.ecolecon.2013.12.003)
14. Weinzettel J, Steen-Olsen K, Hertwich EG, Borucke M, Galli A. 2014 Ecological footprint of nations: comparison of process analysis, and standard and hybrid multiregional input–output analysis. *Ecol. Econ*. **101**, 115–126. (doi:10.1016/j.ecolecon.2014.02.020)
15. MacDonald GK, Brauman KA, Sun S, Carlson KM, Cassidy ES, Gerber JS, West PC. 2015 Rethinking agricultural trade relationships in an era of globalization. *Bioscience* **65**, 275–289. (doi:10.1093/biosci/biu225)
16. Fader M, Gerten D, Thammer M, Heinke J, Lotze-Campen H, Lucht W, Cramer W. 2011 Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. *Hydrol. Earth Syst. Sci.* **15**, 1641–1660. (doi:10.5194/hess-15-1641-2011)
17. Hedenus F, Wirsenius S, Johansson DA. 2014 The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Clim. Change* **124**, 79–91. (doi:10.1007/s10584-014-1104-5)
18. Tilman D, Clark M. 2014 Global diets link environmental sustainability and human health. *Nature* **515**, 518–522. (doi:10.1038/nature13959)
19. Kastner T, Kastner M, Nonhebel S. 2011 Tracing distant environmental impacts of agricultural products from a consumer perspective. *Ecol. Econ*. **70**, 1032–1040. (doi:10.1016/j.ecolecon.2011.01.012)
20. Hoekstra AY, Wiedmann TO. 2014 Humanity's unsustainable environmental footprint. *Science* **344**, 1114–1117. (doi:10.1126/science.1248365)
21. FAO. 2012 FAOSTAT. http://faostat.fao.org.
22. DEFRA. 2013 Experimental statistics: area of crops grown for bioenergy in england and the UK: 2008–2012. https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2012.
23. FAO. 2001 Food balance sheets—a handbook. http://www.fao.org/docrep/003/X9892E/X9892E00.htm.
24. Fertilizers Europe. 2010/2011 Fertilizers Europe forecast of food, farming and fertilizer use. http://www.fertilizerseurope.com.
25. Defra. 2010 The British survey of fertiliser practice: fertiliser use on farm crops for crop year 2010. https://www.gov.uk/government/collections/fertiliser-usage.
26. Heffer P. 2013 Assessment of fertilizer use by crop at the global level 2010-2010/11. http://www.fertilizer.org/En/Statistics/FUBC.aspx.
27. Lassaletta L, Billen G, Grizzetti B, Anglade J, Garnier J. 2014 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environ. Res. Lett.* **9**, 105011. (doi:10.1088/1748-9326/9/10/105011)
28. FAO. 2006 Fertilizer use by crop. http://www.fao.org/ag/agp/fertistat/.
29. FAO. 2005 *Fertilizer use by crop in Ghana*. Rome, Italy: FAO.
30. Tubiello FN, Salvatore M, Rossi S, Ferrara A, Fitton N, Smith P. 2013 The FAOSTAT database of greenhouse gas emissions from agriculture. *Environ. Res. Lett.* **8**, 015009. (doi:10.1088/1748-9326/8/1/015009)
31. IPCC. 2006 Chapter 11: $N_2O$ emissions from managed soils, and $CO_2$ emissions from lime and urea application. In *2006 IPCC guidelines for national greenhouse gas inventories, Prepared by the National Greenhouse Gas Inventories Programme* (eds HS Eggleston, L Buendia, K Miwa, T Ngara, K Tanabe). Japan: IGES.
32. Myhre G *et al.* 2013 Anthropogenic and natural radiative forcing. In *Climate change 2013: the physical science basis. contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds TF Stocker *et al.*) Cambridge, UK: Cambridge University Press.
33. Audsley E, Brander M, Chatterton J, Murphy-Bokern D, Webster C, Williams A. 2009 How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050. Food Climate Research Network/WWF-UK. See http://www.fcrn.org.uk/sites/default/files/WWF_How_Low_Report.pdf.
34. Vellinga TV, Blonk H, Marinussen M, Van Zeist W, Starmans D. 2013 Methodology used in feedprint: a tool quantifying greenhouse gas emissions of feed production and utilization. Wageningen, the Netherlands: Wageningen UR Livestock Research.
35. Williams AG, Dominguez H, Leinonen I. 2014 A simple approach to land use change emissions for global crop commodities reflecting demand. In *Proc. of the 9th Int. Conf. on Life Cycle Assessment in the Agri-Food Sector, San Francisco, California*, pp. 8–10. See http://lcafood2014.org/papers/193.pdf.
36. Hoekstra AY, Mekonnen MM. 2012 The water footprint of humanity. *Proc. Natl Acad. Sci. USA* **109**, 3232–3237. (doi:10.1073/pnas.1109936109)
37. DEFRA. 2013 UK's carbon footprint 1997–2011. Statistics Release. https://www.gov.uk/government/statistics/uks-carbon-footprint.
38. Sandström V, Saikku L, Antikainen R, Sokka L, Kauppi P. 2014 Changing impact of import and export on agricultural land use: the case of Finland 1961–2007. *Agric. Ecosyst. Environ*. **188**, 163–168. (doi:10.1016/j.agee.2014.02.009)
39. Steen-Olsen K, Weinzettel J, Cranston G, Ercin AE, Hertwich EG. 2012 Carbon, land, and water

footprint accounts for the European Union: consumption, production, and displacements through international trade. *Environ. Sci. Technol*. **46**, 10 883 – 10 891. (doi:10.1021/es301949t)

40. Meier T, Christen O, Semler E, Jahreis G, Voget-Kleschin L, Schrode A, Artmann M. 2014 Balancing virtual land imports by a shift in the diet. Using a land balance approach to assess the sustainability of food consumption. Germany as an example. *Appetite* **74**, 20 – 34. (doi:j.appet.2013.11.006)
41. Westhoek H *et al*. 2014 Food choices, health and environment: effects of cutting Europe's meat and dairy intake. *Glob Environ. Change* **26**, 196 – 205. (doi:10.1016/j.gloenvcha.2014.02.004)
42. Friel S *et al*. 2009 Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *Lancet* **374**, 2016 – 2025. (doi:10.1016/S0140-6736(09)61753-0)
43. Tukker A, Goldbohm RA, de Koning A, Verheijden M, Kleijn R, Wolf O, Pérez-Domínguez I, Rueda-Cantuche JM. 2011 Environmental impacts of changes to healthier diets in Europe. *Ecol. Econ*. **70**, 1776 – 1788. (doi:10.1016/j.ecolecon.2011.05.001)
44. Cowell SJ, Parkinson S. 2003 Localisation of UK food production: an analysis using land area and energy as indicators. *Agric. Ecosyst. Environ*. **94**, 221 – 236. (doi:10.1016/S0167-8809(02)00024-5)
45. Gerbens-Leenes PW, Nonhebel S. 2002 Consumption patterns and their effects on land required for food. *Ecol. Econ*. **42**, 185 – 199. (doi:10.1016/S0921-8009(02)00049-6)
46. Barrett J, Owen A, Sakai M. 2011 UK Consumption emissions by sector and origin. Report to the UK Department for Environment, Food and Rural Affairs by University of Leeds.
47. Del Gobbo LC, Khatibzadeh S, Imamura F, Micha R, Shi P, Smith M, Myers SS, Mozaffarian D. 2015 Assessing global dietary habits: a comparison of national estimates from the FAO and the global dietary database. *Am. J. Clin. Nutr*. **101**, 1038 – 1046. (doi:10.3945/ajcn.114.087403)
48. DEFRA. 2012 UK – household purchases 1974 – 2013. Family food datasets. See https://www.gov.uk/government/statistical-data-sets/family-food-datasets.
49. van Middelaar CE, Cederberg C, Vellinga TV, van der Werf HMG, de Boer IJ. 2013 Exploring variability in methods and data sensitivity in carbon footprints of feed ingredients. *Int. J. Life Cycle Assess*. **18**, 768 – 782. (doi:10.1007/s11367-012-0521-9)
50. Hörtenhuber S, Piringer G, Zollitsch W, Lindenthal T, Winiwarter W. 2014 Land use and land use change in agricultural life cycle assessments and carbon footprints: the case for regionally specific land use change versus other methods. *J. Clean Prod*. **73**, 31 – 39. (doi:10.1016/j.jclepro.2013.12.027)
51. Tubiello FN *et al*. 2015 The contribution of agriculture, forestry and other land use activities to global warming, 1990 – 2012. *Glob. Change Biol*. **21**, 2655 – 2660. (doi:10.1111/gcb.12865).