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Assessing pre-pandemic carbon footprint of diet transitions in UK nations and regions

Food supply chains hold significant embodied carbon emissions that need to be mitigated and neutralized. This study aimed to explore the historical Greenhouse Gas (GHG) emissions associated with household food consumption at a local scale i.e., across the eight English regions and the four nations that comprise the United Kingdom (UK). UK EatWell guidelines were used to explore the potential change in emissions and food costs in a scenario of transitions to healthier diets across the study areas. These emissions were calculated based on food consumption data before the advent of the Covid-pandemic i.e., between the years 2001 and 2018. Spatial data analysis was used to explore if the study areas had any significant correlations with respect to the emissions during the study period. The results displayed a potential reduction in GHG emissions for all study areas in the explored scenario. Further impacts include a reduction in household food costs across a majority of the areas during the study period. However, a consistent trend of significant correlations among the study areas was absent. This study concludes that local or regional policymaking should take precedence over national regulations to achieve healthier diets that are both carbon-neutral and affordable for the households.

Key Words: Carbon neutrality; food supply chain; life cycle analysis; United Kingdom; dietary shift; climate change.

1. Introduction

Estimation of GHG emissions from the agricultural sector and related upstream activities is critical for carbon-neutrality as they amount to a third of the total GHG emissions in the world (Gilbert 2012). In the United Kingdom (UK), approximately 7.0% of the total GHG emissions are reported to originate from the agricultural sector (Smith 2012). However, this does not include emissions from backward-linkages and downstream activities along the food supply chain (Audsley et al. 2010). One of the reasons behind this includes the fact that many food items consumed in the UK are imported and as such, sometimes, it is difficult to accurately quantify their environmental footprint. Quantification of these wider emissions is complicated even further owing to the lack of availability of emission factors for all food sub-categories. Still, there have been attempts to quantify food related GHG emissions at national scale in the UK. This includes estimates by the Cabinet Office that show the overall agri-food sector contributing 18.0% of the total to the national GHG emissions (Office 2008). Studies like this are interesting but are limited by their focus on the emissions for the whole country for a particular year only. As such these results may not be meaningful for policymaking at regional or local scale in the UK. Hitherto, there hasn't been any attempt to quantify the temporal differences in emissions between different UK regions and nations. This is mainly because, the calculation of food-related emissions for each region and nation is a complicated task as government statistics report more than 300 different food categories and sub-categories which vary with time and location (Office of National Statistics 2014). Moreover, as discussed above, the changing ratios of food imports from other countries further complicates the calculations due to differences in emission factors for the same food items with different sources. Despite these issues, it is still important and interesting to explore the spatio-temporal variations in food based GHG emissions. This is because, national statistics makes decisions relevant for cabon-neutral policy making at national scale only and may not appreciate provincial or regional differences (Liu et al. 2012). This is important as not all regions and nations share the same socio-economic and environmental status. These differences have been augmented by both international factors such as Brexit and local factors such as rising income gaps between different social strata in these nations (Chen et al. 2018). For instance, one of the most critical issues involving Brexit includes farm subsidies which are critical for the survival of farmers in different parts of the UK (Grant 2016). Similarly, some of the climate related impacts on agriculture in the UK vary with region (Morison and Matthews 2016). Moreover, some segments of the UK 's urban population across different regions lack access to healthy and sufficient food supplies (Wrigley 2002). Ideally, all future policy changes should focus on balancing food security concerns with those of carbon neutrality. While there have been studies at the national scale to determine the environmental impacts of transition to healthier diets at the national scale, studies focusing on local issues and solutions are still more important due to the above-mentioned economic and social disparities between the UK's different regions (Willett et al. 2019). As such, it would be interesting to understand the differences in environmental emissions from UK regions with regard to transition towards healthier diets.

The purposes of this study are three-fold. First, we aim to determine the spatio-temporal variations in weekly Green House Gas (GHG) emissions and costs per capita related to food in different UK nations and English regions between the years 2001 and 2018. The English regions include North West, South West, South East, South West, East, London, Yorkshire & Humber, East Midlands and West Midlands. The UK nations include England, Scotland, Wales and Northern Ireland. We will try to understand if the variations in food based emissions among these regions and nations have been considerable over time. The second purpose is to estimate the weekly per capita emissions and costs based on an ideal mix of different food categories as recommended by the UK EatWell guidelines (Scarborough et al. 2016). The third aim is to understand the end-point impacts of the emissions by estimating how human health and ecosystems are affected because of a shift to healthier diets. We focused on the study period before the Covid pandemic to understand the impacts under normal circumstances as Covid-led disruptions are likely to be temporary and not representative of the usual ground realities.

2. Literature Review

Studies show that the annual food-system emissions amount to 18 Gt CO_2 equivalent globally, representing 34% of total anthropogenic GHG emissions (Crippa et al. 2021). Moreover, diets high in refined sugars, refined fats, oils and meats would be a major contributor to an estimated 80% increase in global agricultural greenhouse gas emissions by 2050 (Tilman and Clark 2014). Transitioning toward more plant-based diets that are in line with standard dietary guidelines could reduce food-related greenhouse gas emissions by 29-70% compared with a reference scenario in 2050 (Springmann et al. 2016). However, this seems difficult given the rising demand of meat from populations across countries such as India and China. Still, research shows that combining technology improvement with dietary shifts, food-based GHG emissions in China could drop by 41.5% compared to the level in 2010 (Li et al. 2016). In India, although most of the GHG emissions originate from livestock and rice production (Vetter et al. 2017) but display significant regional variation (Green et al. 2018). In such countries, improvements in storage and transportation infrastructure is also required to reduce the food related environmental impacts (Mogale et al. 2022; Prajapati et al. 2022).

To avoid undernutrition in low and middle income countries (LMICs), widespread adoption of healthy diets may actually lead to increases in the environmental footprints of the food system (Aleksandrowicz et al. 2019a; Semba et al. 2020). In developed countries, however, a shift to healthier diets may help reduce anthropogenic emissions (Stoll-Kleemann and Schmidt 2017). Of the different food items, animal products account for 43-87% of an individual's environmental burden (Davis et al. 2016). To corroborate this, a study in Denmark discovered that vegetarian and vegan diets generally perform better environmentally compared to a standard Danish diet, with minimal difference between the two no-meat options (Goldstein et al. 2016). These emissions from animal-based diets, however, can be reduced through targeted strategies. For instance, rearing cattle using either corn- or barley-based diets could lead to different environmental impacts across the livestock supply chain (Beauchemin and McGinn 2005). Apart from the supply side interventions, changes in food consumption behaviour among the human populations could also achieve emission reduction. For instance, a study in Hong Kong showed that dietary change from a meat-heavy diet to that following governmental nutrition guidelines could achieve a 67% reduction in livestock-related emissions, thus allowing Hong Kong to achieve the Paris Agreement targets for 2030. While such studies can be conclusive for small regions or countries, more diverse populations and subgroups require dedicated transition strategies (van Dooren et al. 2018; Chaudhary and Krishna 2019). For instance, a study in Norway revealed that willingness to eat less meat was partly determined by the consumers' existing consumption practices (Austgulen et al. 2018) which are often driven by economic and cultural factors (Huan-Niemi et al. 2020). Similarly, a study exploring environmental and nutritional efficiency assessments of diets in 17 Spanish autonomous regions displayed significant regional variations driven by differences in climate, culture and lifestyle (Esteve-Llorens et al. 2020).

For the UK, a study comparing meat-eaters, fish-eaters, vegetarians and vegans discovered that dietary GHG emissions in self-selected meat-eaters were twice as high as those among the vegans (Scarborough et al. 2014b). Another study assessed the embodied environmental impacts of fertilissers in the production of bread in the UK (Goucher et al. 2017). Similar studies show that healthier diets in the UK could delay or avert deaths thus displaying an alignment among public health and climate change dietary goals (Friel et al. 2009; Scarborough et al. 2012). Another study shows that diet related GHG emissions in the UK could be reduced by 17-40% through behavioural change (Green et al. 2015). Studies however point out towards deficiencies in national food-related policy making in the UK and the need for a more granular approach to uncover finer details (Parsons 2020; Benthem de Grave et al. 2020). For a regional approach, a recent study uncovered the economic and environmental impact of shift in consumption under healthy eating guidelines in Scotland only (Allan, Comerford, and McGregor 2019). Apart from this, another study compared the city regions of Bristol in the UK and Vienna in Austria in terms of dietary land footprint (Vicente-Vicente et al. 2021). To the best knowledge of the authors, this is the first spatio-temporal assessment of economic and environmental impacts of diets changes in UK nations and English regions.

3. Methods

3.1 Goal and scope definition

In this paper we will employ environmental accounting of different foods in the UK that are consumed at home by estimating GHG emissions through Life Cycle Analysis (LCA) (Lake et al. 2015; Koh et al. 2013). A recent review shows that of all the different analytical and simulation methods, LCA "is exclusively used to analyse environment-related issues" for sustainable food supply chains (Zhu et al. 2018a). The LCA methodology has been in use since the 1960s and is a robust framework used to determine the environmental impacts of a material, product or service (Ali et al. 2020). Life Cycle Assessment (LCA) is a robust and sophisticated technique that has been used in a variety of studies in the past to assess the impact of diets on the environment at national scales (Heller, Keoleian, and Willett 2013; Muñoz, Milà i Canals, and Fernández-Alba 2010). Other alternatives include techno-environmental analysis and econometric modelling to estimate the socio-economic assessments of dietary changes. However, for environmental impact assessments, LCA is a better alternative due to the level of detail in the analysis and results. Similarly, LCA follows internationally recognized standards (ISO 14040 and 14044) which lends further credibility to the modelling. A recent review corroborates that a lifecycle approach is integral to the traceability of environmental sustainability in agri-food systems (Corallo et al. 2020).

The system boundary includes the food supply chain from production to the retail distribution centre. The Green House Gas (GHG) emissions factors were expressed in the units of kg CO_2-eq per 100 grams of food consumed (i.e., kg of GHG weighted by global warming potential over a 100-year time frame, with carbon dioxide weighted as 1, methane weighted as 25 and nitrous oxide weighted as 298). The emission factors were multiplied with the food consumption data reported in the units of 100 grams per person per week to report the final results in the units of kg CO_2-eq per person per week. A set of emission factors had already been calculated for a range of foods consumed in the UK and was made available on request with density adjustments made for food imports and to account for differences in food production and consumption densities (Ali, Liu, and Zhang 2021; Scarborough et al. 2014a). These parameters themselves were based on an earlier study that reported GHG emissions for different food commodities consumed in the UK (Audsley et al. 2010). All calculations can be obtained from the first author upon request.

For this study, we segmented different food types into 5 broad categories defined by UK EatWell to compare the differences in current eating behaviour from the recommended quantities of foods. These food categories include (a) Fruits and vegetables, (b) Proteins, (c) Dairy and alternatives, (d) Starchy carbohydrates and (e) Foods high in fats and sugars. As such, drinks (alcohol, soft drinks, etc.) and 'other' items in the data were ignored for the analysis due to their low carbon intensities and the challenge of classifying them into the above-mentioned food categories.

3.2 Data sources

Inventory data for consumption statistics was obtained from secondary resources that reported food consumption and expenditure for different UK regions and nations over time. Most of the data was collected using latest available statistics from UK's Family Food datasets that report data for the years 2001 through to 2018 (DEFRA 2018). The figures in Family Food are sourced from The Living Costs and Food Survey run by the Office for National Statistics (Office of National Statistics 2014). As noted above, these datasets report food and drinks that are consumed within the households. This data is collected each year using voluntary sample survey of private households using a list of major food categories which are then further disaggregated into their respective sub-food types amounting to more than 300 items. All data is available in the units of grams or milli-litres (e.g., fruit juices) per person per week which was converted for this study into the units of 100 grams per person per week after using density adjustments and unit conversions based on literature review. As mentioned above, this data can be obtained from the first author upon request.

3.3 Scenarios

Emissions from two different scenarios were calculated and compared with each other

a) GHG emissions from household food consumption were estimated based on the available statistics up to the year 2018 assuming a Business As Usual (BAU) scenario. Emissions for all UK regions and nations were calculated separately.
b) GHG emissions based on the recommended portion sizes (as per EatWell recommendations) was calculated for the different regions and nations in the UK over

time. Differences in monetary costs were also explored to understand the economic impact of transition to a healthier diet.

The results will be displayed as a difference between the two scenarios described above. Changes in emissions as a result of transition to healthier diets will be quantified to account for impacts on human health and ecosystems using the ReCiPe method.

3.4 Limitations

While calculating the emissions for different years we assumed the emission factors to have remained constant. This is because the largest variation in emissions is caused by changes in quantities and sources of import categories from Rest of the World (Row) areas, which, in contrast to imports from EU countries, haven't changed drastically over the studied period. This is shown in Figure 1 below which shows changes in imports of major food categories from EU countries and RoW between the years 2000 and 2018 as reported by Food and Agriculture Organisation of the United Nations Statistics (FAOSTAT) (FAOSTAT 2019). In contrast, emission factors for most of the import items from the EU countries are similar to that for locally produced substitutes in the UK. Moreover, our focus of attention in this study is the regional disparity in emissions and data for the distribution of food imports across English regions is difficult to obtain. A study involving a particular food category might be able to trace regional import flows but tracking each of the more than 300 sub-categories of food items across 18 years in so many different regions is beyond the scope of this study.

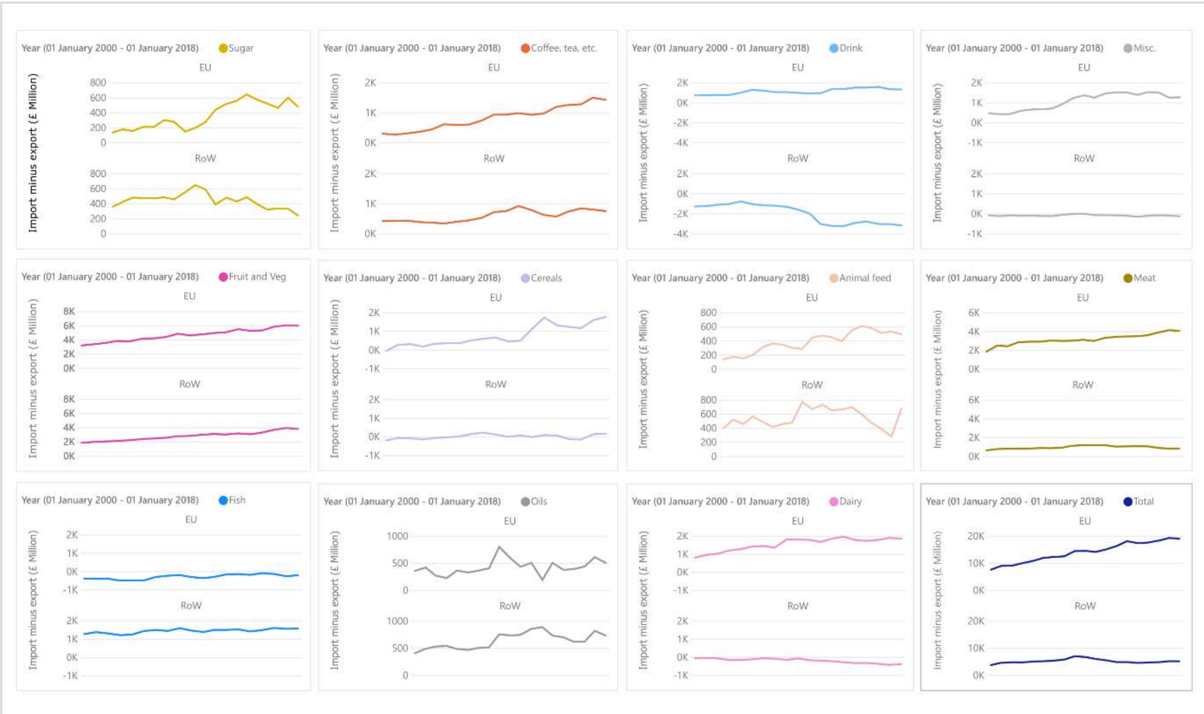

Figure 1. Change in imports to UK from EU and RoW between 2000 and 2018.

4. Results and Discussion

4.1 Greenhouse Gas emissions

Figure 2a and 2b displays the change in GHG emissions for English regions and UK nations between the years 2001 and 2018 for the scenario that the diets transition from current patterns to those based on UK Eatwell recommendations. The figures present the results in the form of a hierarchy of estimated emission reduction potential. Here, for each individual year, the region with the least expected change in emissions has been presented in the top band and the region with the greatest possible reduction has been presented in the lower most band. For figure 2a it can be seen that for most of the years during the study period the greatest reduction in emissions would have occurred in the North East region as shown by the light blue ribbon. On the other hand, the least amount of emission reduction would have occurred in London had UK Eatwell recommendations been followed, as indicated by the yellow ribbon. Data analysis shows that the inherent reason behind this difference is based on food consumption habits where people in the North East consume much more meat in their diets than those in London. Similarly, figure 2b shows that for most of the years during the study period, the nation of Northern Ireland had the greatest emission reduction potential whereas England had the least emission reduction potential. These differences among the nations also emanate from the underlying variations in food consumption behavior.

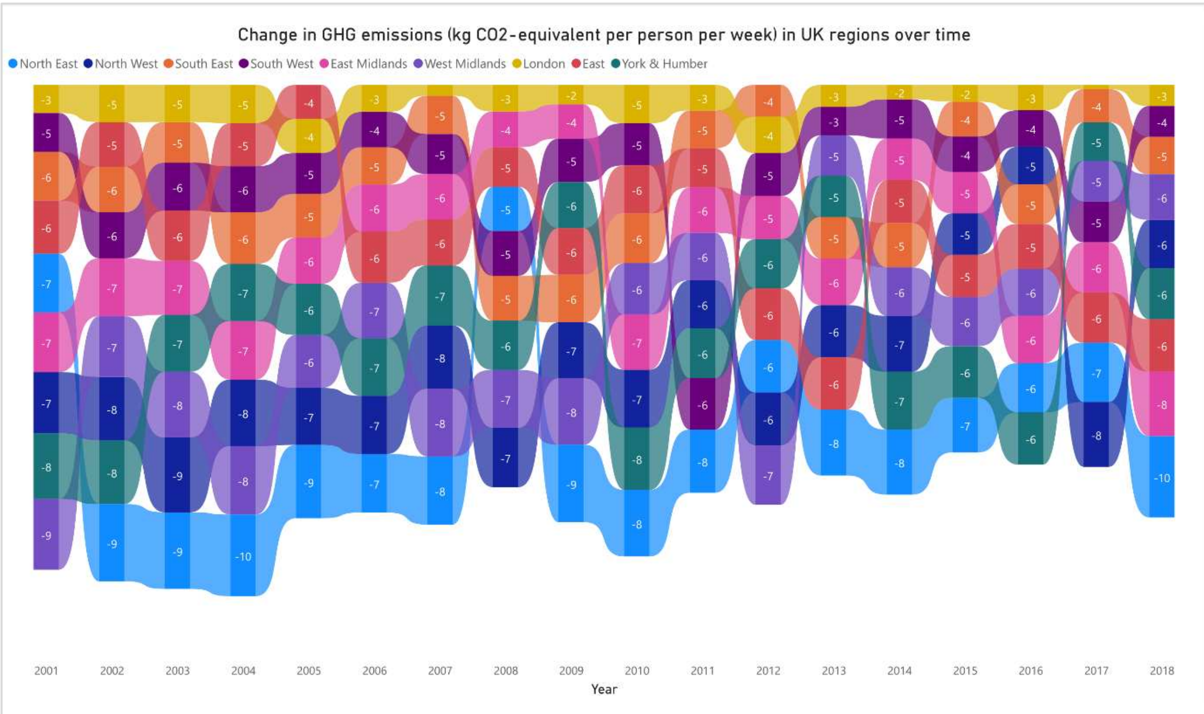

Figure 2a. Change in per capita weekly GHG emissions in English regions resulting from a change in diet patterns to those based on UK Eatwell recommendations. Decimal places could not be shown due to font size limitations.

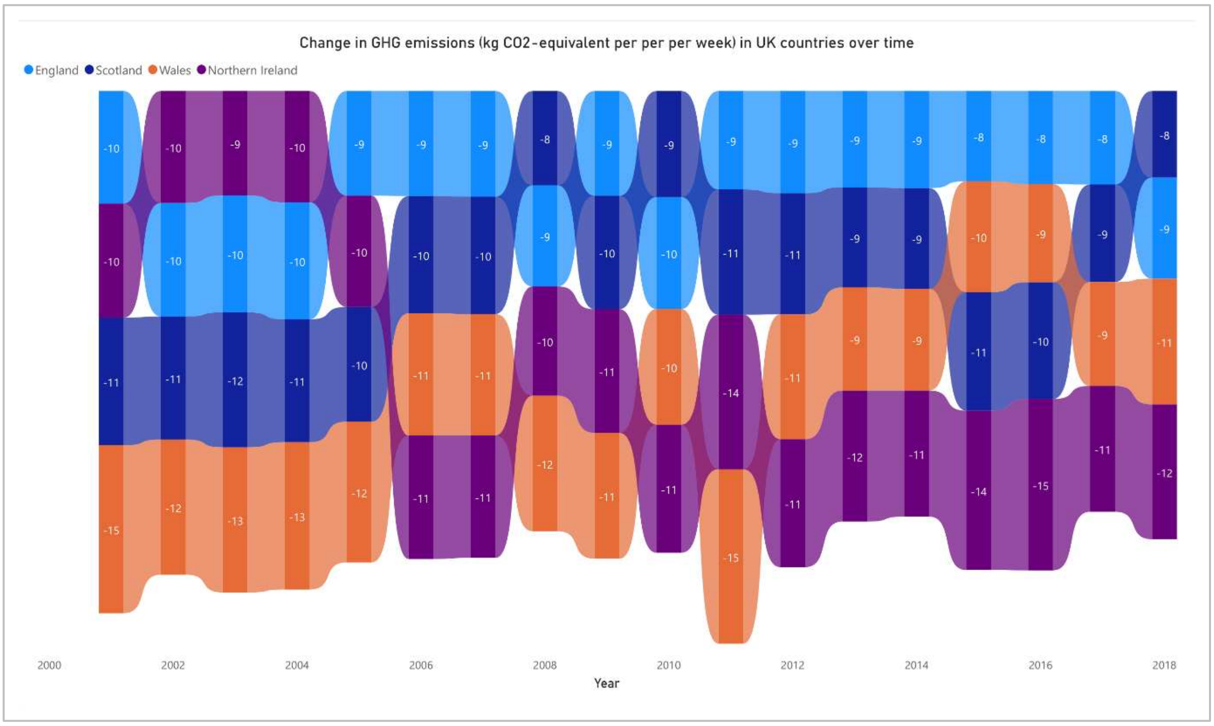

Figure 2b. Change in per capita weekly GHG emissions in UK nations resulting from a change in diet patterns to those based on UK Eatwell recommendations. Decimal places could not be shown due to font size limitations.

For a more thorough analysis, spatial correlation of the emissions from the regions was assessed for all years during the study period. For correlations, we estimated global and local Maron's I using the spatial lag model with the help of GeoDa software (Anselin, Syabri, and Kho 2010) . Previous efforts to quantify spatial autocorrelations based on regional emissions include a study in China where CO_2 emissions from different provinces were used in a spatial lag model (Shi et al. 2019). We have used a similar model as it can help us understand the spatial dependency between different geographical locations and for the present study it is more relevant than time series models. Results show that there is no significant spatial correlation as measured by the global Maron's I. It is pertinent to mention here that local Moran I and global Moran I are used for different purposes and their exact use depends on the assumptions one makes. Global Moran I implies that one single statistic can account for all of the data whereas local Moran I will return local clusters that may or may not be correlated. In other words, the global Moran statistic only tells us about overall pattern, whether there is any clustering but it does not tell us about where this clustering is, or what it looks like. Consequently, global Moran

I may tell that the variable is random distributed while in fact we may have cluster in the data, because it is an average measurement. In other words, some variables may be locally strongly autocorrelated, but display no correlation over a slightly larger radius (Oliveau and Guilmoto 2005). Local Moran I can address the shortcomings of the global Moran's I by capturing these clusters. As such we measured the local spatial autocorrelations for all years in the study period. It is important to note here that the nations of Northern Ireland, Scotland and Wales were also considered as regions in this analysis to account for disparities between adjacent areas. Figure 3 shows the results based on different levels of significance based on the Bonferroni criterion. Significant local clusters were formed in only seven years during the study period. It can be seen that different regions cluster together in different patterns from one year to another and no two regions were consistently correlated from one year to another based on their food-based emissions. This serves to indicates that the regions vary from each other significantly which is caused mainly due to underlying differences in food consumption. This supports our premise that the differences among the regions and the nations are large enough to warrant customized policy making for food-based emission reduction. This is because the food behavior itself is a function of socio-economic variables which vary across these regions. As such each region requires policies tailored according to their subtle as well as noticeable sensitivities and behaviors.

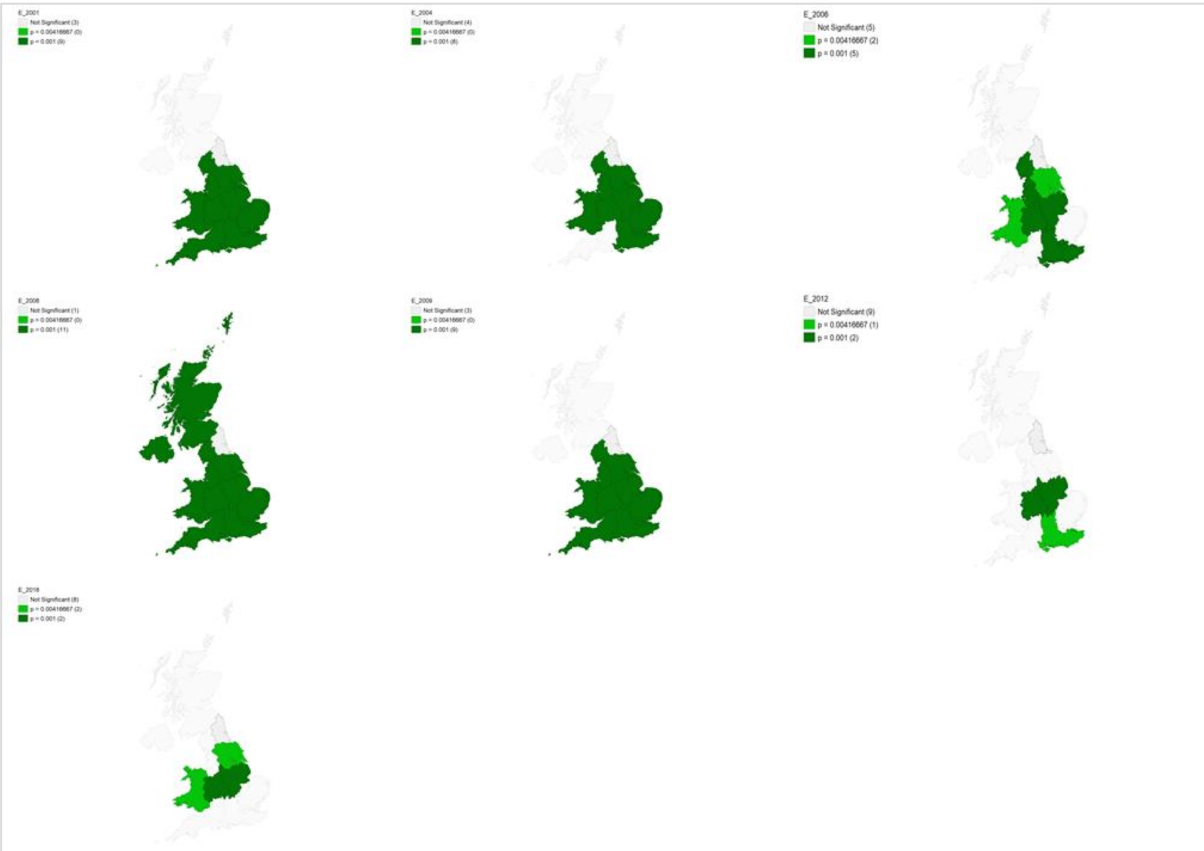

Figure 3. Local auto-correlations for emissions from UK nations (Scotland, Wales and Northern Ireland) and English regions between 2001 and 2018. Areas shaded dark green show correlations with greater statistical significance using Bonferroni criterion.

4.2 Implications for household finances

A rebalancing of the diets would also have implications for food costs borne by the households. As such it would be interesting to observe the change in per capita weekly costs as a result of a change in diets from current patterns of consumption to those based on UK Eatwell recommendations. The results have been presented in Figure 4a and 4b which display the change in weekly per capita expenditure on food for different regions and nations over time with a shift towards healthier diets based on UK EatWell recommendations. Since the figures compares data for each region or nation across individual years, the values haven't been normalized for a region or base year. Inflation adjustment is also challenging as relevant inflation data at a nation scale. It can be seen that for most of the regions across most of the years there would have been a reduction in food expenditure. Figure 4a shows that this reduction would have been the greatest in regions such as West Midlands and the North East. On the other hand, there would have been an increase in expenditure for residents in London had UK Eatwell recommendations been followed which could be due to higher cost of living and possibly greater physical distance from agricultural areas. Figure 4b also shows that except for the year 2002 in Scotland, the year 2003 in Wales and the years 2015 and 2017 in England, households could have saved food costs if UK EatWell recommendations had been followed.

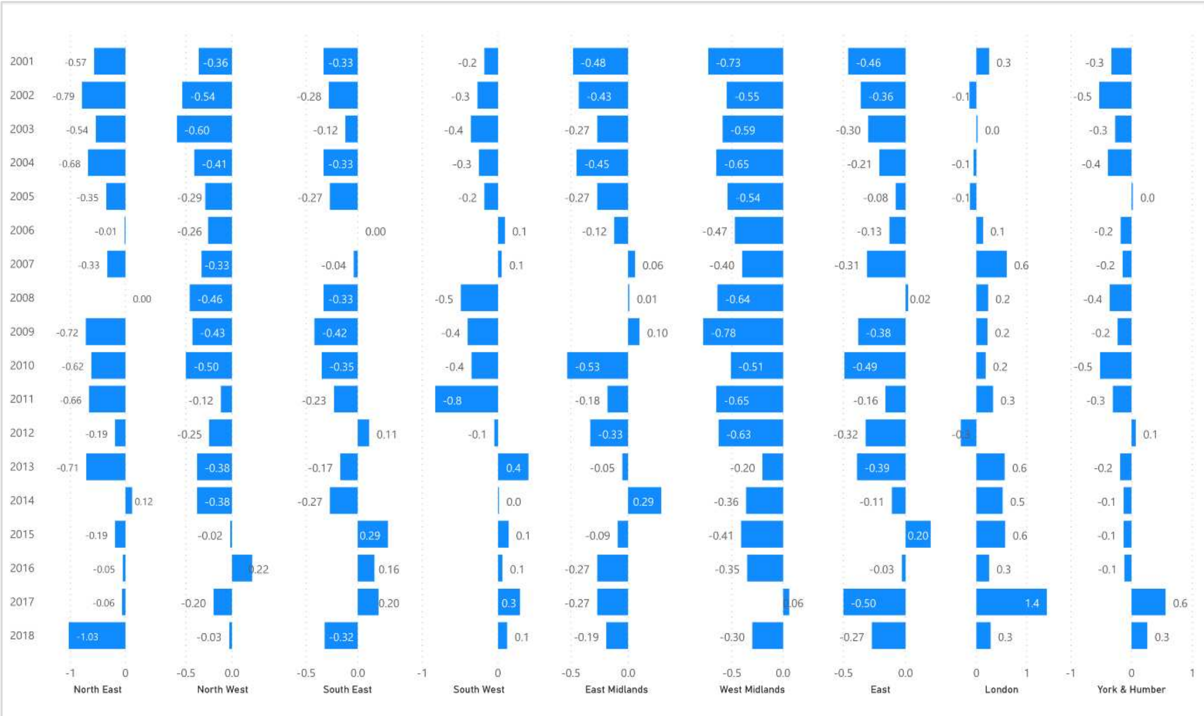

Figure 4a. Variation in per capita weekly expenditure per person per week in £s in English regions.

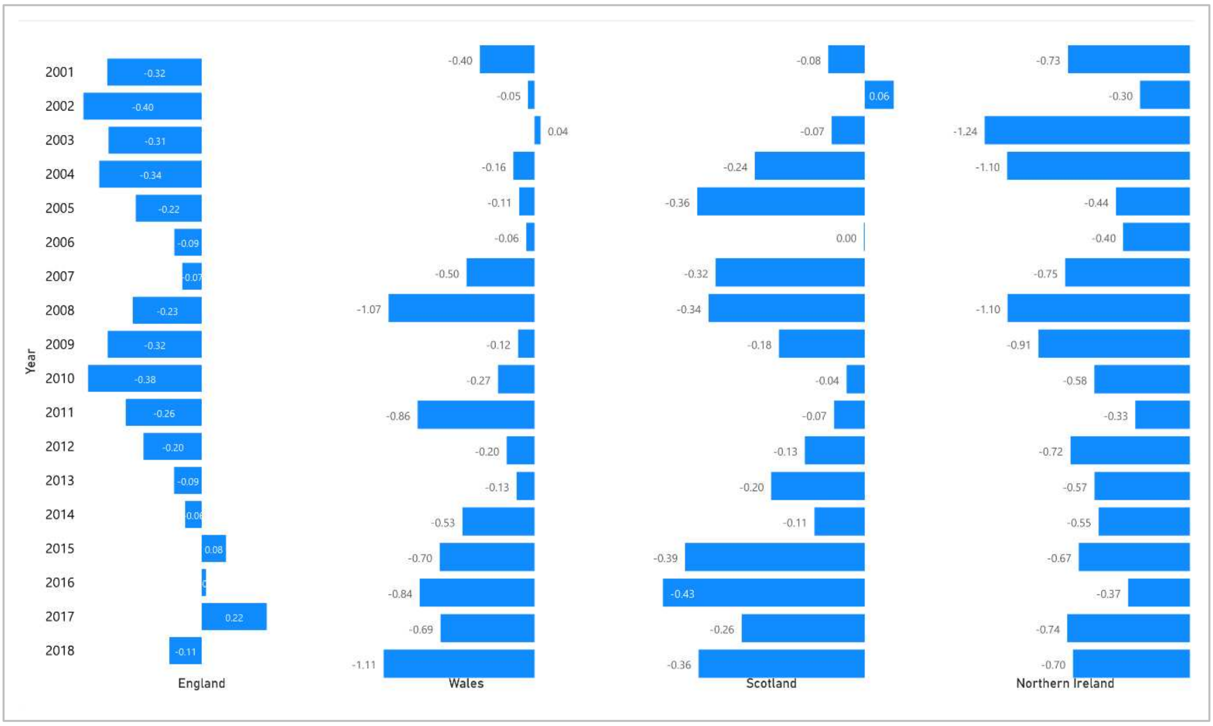

Figure 4b. Variation in per capita weekly expenditure per person per week in £s in UK nations.

4.3 Implications for human health and ecosystem services

As mentioned above, the health impacts of GHG emissions can be calculated using DALYs. DALY represents the years of life lost and the number of years lived as a disabled person due to the impact of emissions, and it is based on an approach developed by the World Health Organization (WHO) (Reza, Sadiq, and Hewage 2014). Similarly, the impacts on terrestrial and freshwater ecosystems can be measured based on species extinctions as measured in the units of species-years. These end-point impacts for all UK regions and nations for the years between 2001 and 2020 have been presented in Figures 5a, 5b and 65c below. These are based on actual data for the years between 2001 and 2018 and forecasts for the years 2019 and 2020 as presented above. All results have been shown below using the ‘hierarchical’ perspective which is the default in most of the LCA studies (Weidema 2015). In Figures 5a through 5c, it can be seen that the trend lines for all regions are similar to those shown in Figures 2a and 2b as they are based on fixed conversion factors. In other words, all figures show savings in human as well as ecosystem health as a consequence of emission reductions in the studies regions.

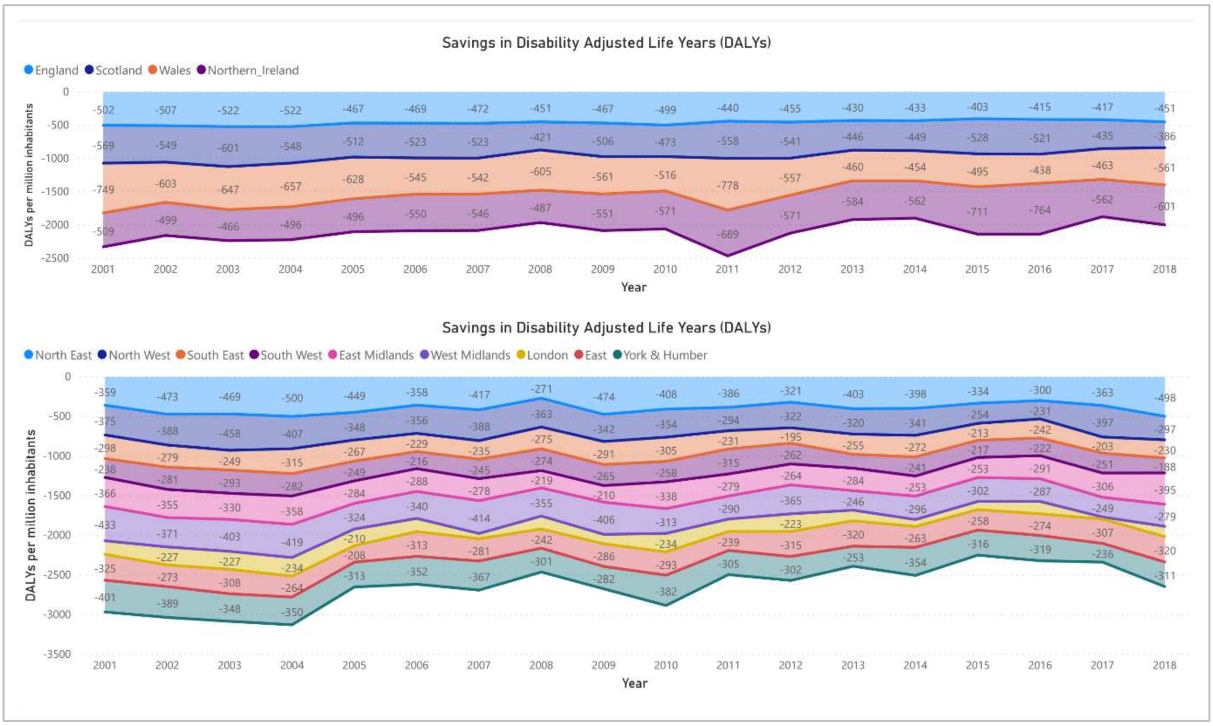

Figure 5a. Reduction in health impacts of GHG emissions in DALYs per million people for English regions and UK nations.

As mentioned above, using the measure of DALY as a proxy to assess the impact of GHG emissions on human health is a widely used LCIA technique (Cobiac and Scarborough 2019; Eckelman and Sherman 2018). For further clarification, DALY is the number of disability years caused by exposure to chemicals or pollutants multiplied by the “disability factor”, a number between 0 and 1 that describes severity of the damage (0 for being perfectly healthy and 1 for being fatal/loss of life) (Schuur et al. 2009). Figure 5a in the manuscript shows the reduction in this potential health damage due to an improvement in diets and the impact is shown per million people for greater clarity.

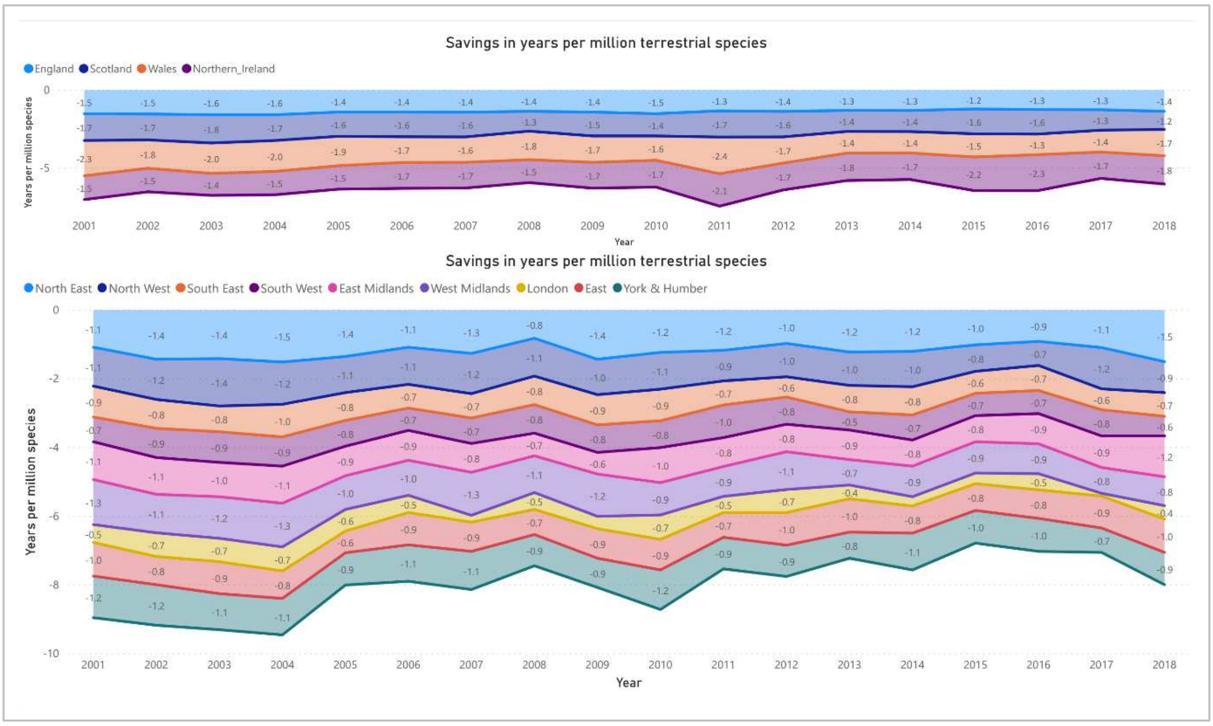

Figure 5b. Reduction in terrestrial ecosystem impacts of GHG emissions in life-years per million species for English regions and UK nations.

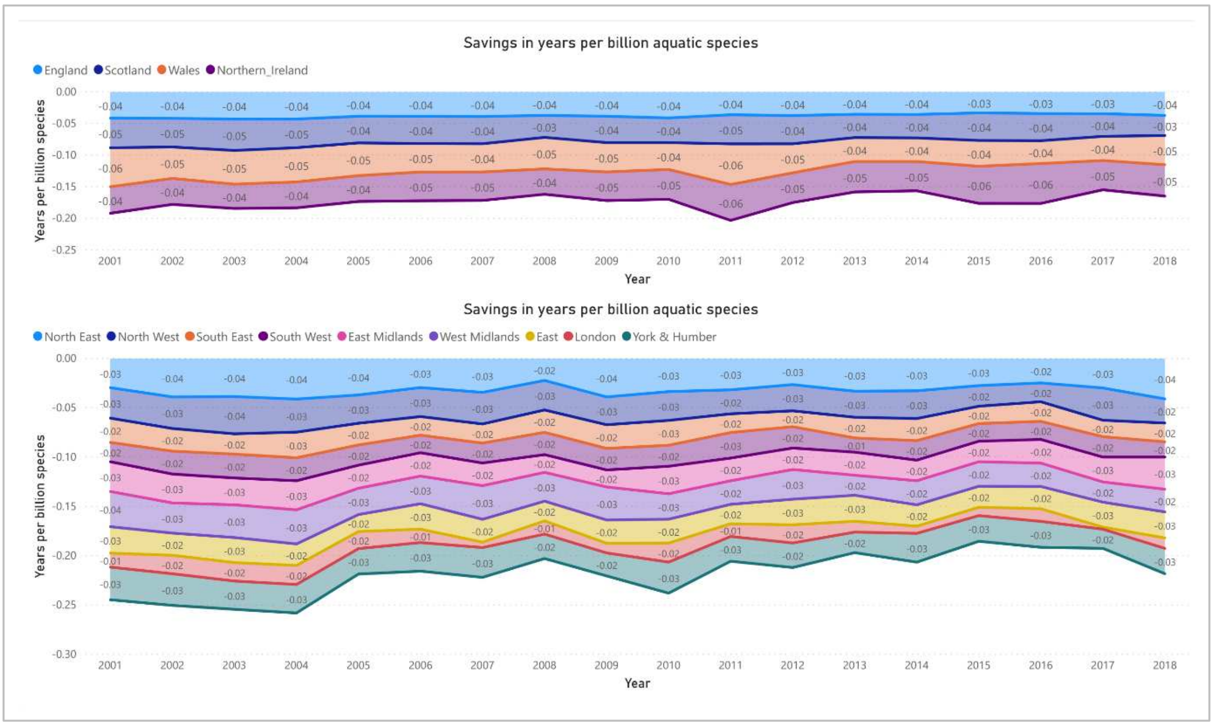

Figure 5c. Reduction in aquatic ecosystem impacts of GHG emissions in life-years per billion species for English regions and UK nations.

The impacts on terrestrial and freshwater ecosystems are standard LCIA categories which express potentially disappeared fraction of species (PDF) integrated over space and time in m^2.years. A detailed explanation of the methodology to measure them can be seen here for instance (Huijbregts et al. 2017). As most LCA studies use pre-determined characterisation factors that express the PDF over area and time, a repetition of the detailed steps to measure each of the standard indicators/impact categories is unnecessary (Rashedi and Khanam 2020; Goronovski et al. 2018; Heidari et al. 2017). Figures 5b and 5c show the reduction/saving in this loss of species as a consequence of a shift towards healthier diets.

As shown in figures 5a to 5c display the difference or savings in shifting from pre-existing diets to those recommended by UK Eatwell. In figure 2b, a positive difference would show an increase in emissions whereas a negative difference would indicate emission reduction. Similarly, in Fig 5a, a positive difference would indicate a surplus number of lives lost (something undesirable) and a negative number would indicate number of lives *not* lost or the number of lives saved (which is actually desirable). The same logic applies to figures 5b and 5c. Mathematically this can be written as follows:

$$\text{Net Emissions} = \text{Emission}_{\text{Baseline}} - \text{Emission}_{\text{Eatwell}} \quad \text{(negative figures are desirable)}$$

$$\text{Net Lives Lost} = \text{Lives Lost}_{\text{Baseline}} - \text{Lives Lost}_{\text{Eatwell}} \quad \text{(negative figures are desirable)}$$

$$\text{Net Species Lost} = \text{Species Lost}_{\text{Baseline}} - \text{Species Lost}_{\text{Eatwell}} \quad \text{(negative figures are desirable)}$$

4.4 Discussion and comparison with other studies

Interest and investment in carbon-neutral food supply chains has been increasing with the passage of time (Mogale, Cheikhrouhou, and Tiwari 2020). The reasons behind this phenomenon include a changing dietary landscape where consumers have become more conscious and vocal in favour of sustainable foods. Some of the environmental challenges emanating from these carbon emissions include climate change, air pollution, loss of biodiversity and a reduction in ecosystem services. These issues have been complemented with those of food safety and security emanating from external supply chain shocks such as Brexit, the swine flu virus and the Covid-19 pandemic. Some of these disruptions jolted food supply chains in a way that led to food shortages and rationing for many households in the UK (Hobbs 2020). There is a growing realization that the urban food systems are particularly vulnerable to supply chain shocks. Consequently, policymakers are trying to find innovative solutions to future-proof sustainable supply of healthy food to all communities. There have been efforts to suggest planetary diets for different areas of the world by optimising the environmental and nutritional requirements in such areas (Willett et al. 2019; Zhu et al. 2018b). However, such policy suggestions have been criticized for being unaffordable for some segments of the society (Temple and Steyn 2011). Similarly, despite an increasing interest in the topic of urban and regional food systems, there is a limited understanding of possible policy solutions. Prominent issues include, lack of a clear consensus regarding benchmarking resilience and sustainability indicators for the food supply chains (Yakovleva, Sarkis, and Sloan 2012). This is understandable because geographical locations differ from each other in terms of their social, economic and environmental needs. For instance, previously researchers have tried to develop an ideal food system that aims to meet the challenges of environmental, nutritional, and economic constraints through mathematical optimization. Yet, it has been acknowledged that most of these models fail to account for spatial and temporal variations in diet consumption (Drewnowski 2020). As such, there is a paucity of studies that assess carbon-neutrality of food consumption at a local scale. In other words, the number of studies exploring impact of changes in food consumption on emissions at regional scales across different years are relatively rare. Still, there have been attempts to understand carbon, water and ecological footprint of shifts in household food consumption for different nations. This includes, for instance, a modelling exercise in the UK that discovered that on average a saving of 1.6 kg CO_2-eq/day could be achieved if the UK EatWell recommendations were followed (Scheelbeek et al. 2020). This aligns well with this study which shows a per capita saving of 1.49 kg CO_2-eq/day as an average for the UK nations and 0.86 kg CO_2-eq/day as an average for English regions for the studied period. Another study in the UK attempted to optimise ideal diets for different income groups and concluded that diets of different income quintiles might have similar GHG emissions, but the source these emissions can vary due to differences in consumption of various food categories (Reynolds et al. 2019). This study also finds that while the average emissions from different regions and nations might be similar, the underlying consumption of different food categories can result in a wide range of emission savings as shown in Figures 2a and 2b. Similarly, a study for the European Union (EU) concluded that a shift to healthier diets could reduce the environmental impacts by 8% (Tukker et al. 2011). While these results encourage the adoption of national diet guidelines for emission reduction, in some developing countries there might actually be an increase in emissions if dietary guidelines are to be followed entirely. For instance a recent study in India discovered that meeting healthy guidelines would actually increase GHG emissions by 3-5%, especially in rural areas which have a greater proportion of low-income households (Aleksandrowicz et al. 2019b). Similarly, another study in China discovered that if all Chinese follow healthy diets rather than their existing diets, the GHG emissions would actually increase by 7.5% (He et al. 2019). Interestingly, the direction of change in GHG emission as a result of dietary change can vary depending on resource inputs for agricultural production. For instance, a study for the United States of America (USA) discovered that dietary shifts to government recommendations with low calorie intakes could actually increase GHG emissions by 11% which is a reflection of resource intensive healthier food sources such as fruits and vegetables (Tom, Fischbeck, and Hendrickson 2016). This serves to show that policy changes may have counterintuitive results unless ground realities have been accounted for. This is all the more reason why local-scale perspectives should be taken into account food policy making for carbon-neutrality.

In this paper we took a local perspective by focusing on the English regions and the nations within the United Kingdom. This is important as national level statistics represent aggregate sums and for individual years only which make it "challenging to understand fine-scale behavioural change over shorter timeframes" (Benthem de Grave et al. 2020). As such they fail to highlight the spatio-temporal differences in food consumption behaviour and associated emissions for effective policymaking. This is crucial as a single mitigation policy would potentially yield varying results across the different regions. As an example, the instances of avoidable and food related health conditions are more prevalent in the Northern regions than in the South of the UK (Baker 2022). Clearly, the food policy has not addressed the underlying inequalities which drive these health conditions. Realizing this issue, in the year 2020, the food policy was devolved to the governments of England, Wales, Scotland and Northern Ireland. Further devolution is needed at regional scales as, for instance, studies show that food policy making in the England is dispersed and opaque and "the use of an aggregated government website makes it difficult to identify information" (Parsons 2020). This lends further support to the need for a more localised focus in food-related research and policy-making. The most recent independent review of the governments' food strategy calls for developing "local food strategies, with reference to national targets and in partnership with the communities they serve" (NFS 2021).

As food choices depend on local contexts, effective policy design could choose a combination of supply and demand side measures for a sustainable behavioural change. These choices include, restricting availability of hot food takeaways near schools for obesity prevention, imposing sugar taxes, effecting display layouts of grocery stores, developing local food standards for school and office meals, etc (von Philipsborn et al. 2019). In essence, a local or community-based perspective is essential before choosing and implementing any of the policy measures (Orr and McCamley 2017). Apart from behavioural changes, a local perspective is also important because it allows for greater pressure from the community for transparency and traceability in agri-food supply chains (Golini et al. 2017). This, in turn, facilitates greater cooperation among the producers and the cooperatives for sustainability at source by measures such as post-harvest food loss reduction (Despoudi et al. 2018).

5. Conclusions

This study was aimed at understanding the life cycle impacts of transition to healthier diets for people in different regions of England and different nations in the UK over time. We focused on the years before the Covid pandemic to understand these impacts under normal circumstances. The results of the study show that for all regions there would have been a reduction in emissions had UK Eatwell recommendations been followed. However, spatial auto-correlations confirmed that there exist significant differences between the regions in terms of the level of emission reductions that could have been achieved. This was accompanied by an analysis of the adjustments to the consumption of major food types required on a on a weekly per capita basis for all regions using the average statistics for the 18-year period of study. Similarly, differences were discovered in terms of the expenditure that could have been mitigated as a result of transition to healthier diets. All of this points to the fact that the studied regions differ from each other and require different responses to food sustainability demands. Thus all future public-health policy making should appreciate local differences while designing a carbon-neutral and affordable food provision strategy. To the best knowledge of the authors, this is the first study exploring spatio-temporal assessment of changes in emissions and expenditures for different UK regions. Future studies can explore the differences in tradeoffs between resilience and sustainability of food supply chains for these regions to aid a more targeted and customized policymaking.

A limitation of this study is the use of the same emission factors for all regions and nations and for the studied period. This was mainly due to a lack of availability of data pertaining to the portion of imported food consumed for different locations over time. Similarly, the emission factors were assumed to be constant for all years from 2001 and 2018 as the ratio of food imports from RoW to imports from EU or local production didn't vary drastically. Moreover, data for household consumption was the focus of this study and as such 'eating out' activities were ignored while collecting data. Future research can build on the LCA used in this analysis to estimate the upstream and downstream impacts of dietary shifts related to a particular food category, using other variations of LCA techniques such as hybrid-LCA or input-output tables. Similarly, further granularity can be achieved using a city-scale perspective starting from larger cities such as London, Birmingham, Edinburgh etc. Further refinement can be added by using primary data instead of relying on statistics from government reports only.

5. Acknowledgments

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6. Data availability

The authors confirm that the data supporting the findings of this study are available within the supplementary materials.

7. References

Aleksandrowicz, L., R. Green, E. J. M. Joy, F. Harris, J. Hillier, S. H. Vetter, P. Smith, B. Kulkarni, A. D. Dangour, and A. Haines. 2019a. "Environmental impacts of dietary shifts in India: A modelling study using nationally-representative data." Review of. *Environment international* 126:207-15. doi: https://doi.org/10.1016/j.envint.2019.02.004.

Aleksandrowicz, Lukasz, Rosemary Green, Edward JM Joy, Francesca Harris, Jonathan Hillier, Sylvia H Vetter, Pete Smith, Bharati Kulkarni, Alan D Dangour, and Andy Haines. 2019b. "Environmental impacts of dietary shifts in India: A modelling study using nationally-representative data." Review of. *Environment international* 126:207-15.

Ali, M., L. Liu, and J. Zhang. 2021. "Exploring spatio-temporal variations in environmental impacts from eating out in the United Kingdom." Review of. *Sci Total Environ* 801:149540. doi: 10.1016/j.scitotenv.2021.149540.

Ali, Mustafa, Lingxuan Liu, Yong Geng, and Shahid Khokhar. 2020. "Emergy based sustainability evaluation of a hydroelectric dam proposal in South Asia." Review of. *Journal of Cleaner Production* 264:121496.

Allan, Grant, David Comerford, and Peter McGregor. 2019. "The system-wide impact of healthy eating: Assessing emissions and economic impacts at the regional level." Review of. *Food Policy* 86:101725. doi: https://doi.org/10.1016/j.foodpol.2019.05.008.

Anselin, Luc, Ibnu Syabri, and Youngihn Kho. 2010. "GeoDa: an introduction to spatial data analysis." In *Handbook of applied spatial analysis*, 73-89. Springer.

Audsley, Eric, M Brander, Julia C Chatterton, Donal Murphy-Bokern, C Webster, and Adrian G Williams. 2010. "How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope reduction by 2050. Report for the WWF and Food Climate Research Network." Review of.

Austgulen, M. H., S. E. Skuland, A. Schjoll, and F. Alfnes. 2018. "Consumer Readiness to Reduce Meat Consumption for the Purpose of Environmental Sustainability: Insights from Norway." Review of. *Sustainability* 10 (9). doi: 10.3390/su10093058.

Baker, Carl. 2022. "Briefing paper - Obesity." In.: House of Commons.

Beauchemin, K. A., and S. M. McGinn. 2005. "Methane emissions from feedlot cattle fed barley or corn diets." Review of. *Journal of Animal Science* 83 (3):653-61.

Benthem de Grave, Remco, Niki A. Rust, Christian J. Reynolds, Anthony W. Watson, Jan D. Smeddinck, and Diogo M. Souza Monteiro. 2020. "A catalogue of UK household datasets to monitor transitions to sustainable diets." Review of. *Global Food Security* 24:100344. doi: https://doi.org/10.1016/j.gfs.2019.100344.

Chaudhary, Abhishek, and Vaibhav Krishna. 2019. "Country-Specific Sustainable Diets Using Optimization Algorithm." Review of. *Environmental science & technology* 53 (13):7694-703. doi: 10.1021/acs.est.8b06923.

Chen, Wen, Bart Los, Philip McCann, Raquel Ortega-Argilés, Mark Thissen, and Frank van Oort. 2018. "The continental divide? Economic exposure to Brexit in regions and countries on both sides of The Channel." Review of. *Papers in regional science* 97 (1):25-54.

Cobiac, Linda J, and Peter Scarborough. 2019. "Modelling the health co-benefits of sustainable diets in the UK, France, Finland, Italy and Sweden." Review of. *European journal of clinical nutrition* 73 (4):624-33.

Corallo, A., M. E. Latino, M. Menegoli, and P. Pontrandolfo. 2020. "A systematic literature review to explore traceability and lifecycle relationship." Review of. *International Journal of Production Research* 58 (15):4789-807. doi: 10.1080/00207543.2020.1771455.

Crippa, M., E. Solazzo, D. Guizzardi, F. Monforti-Ferrario, F. N. Tubiello, and A. Leip. 2021. "Food systems are responsible for a third of global anthropogenic GHG emissions." Review of. *Nature Food* 2 (3):198-209. doi: 10.1038/s43016-021-00225-9.

Davis, K. F., J. A. Gephart, K. A. Emery, A. M. Leach, J. N. Galloway, and P. D'Odorico. 2016. "Meeting future food demand with current agricultural resources." Review of. *Global Environmental Change-Human and Policy Dimensions* 39:125-32. doi: 10.1016/j.gloenvcha.2016.05.004.

DEFRA. 2020. "Family food datasets." Accessed 06 September. https://www.gov.uk/government/statistical-data-sets/family-food-datasets.

Despoudi, S., G. Papaioannou, G. Saridakis, and S. Dani. 2018. "Does collaboration pay in agricultural supply chain? An empirical approach." Review of. *International Journal of Production Research* 56 (13):4396-417. doi: 10.1080/00207543.2018.1440654.

Drewnowski, Adam. 2020. "Analysing the affordability of the EAT–Lancet diet." Review of. *The Lancet Global Health* 8 (1):e6-e7.

Eckelman, Matthew J, and Jodi D Sherman. 2018. "Estimated global disease burden from US health care sector greenhouse gas emissions." Review of. *American journal of public health* 108 (S2):S120-S2.

Esteve-Llorens, Xavier, Mario Martín-Gamboa, Diego Iribarren, Maria Teresa Moreira, Gumersindo Feijoo, and Sara González-García. 2020. "Efficiency assessment of diets in the Spanish regions: A multi-criteria cross-cutting approach." Review of. *Journal of Cleaner Production* 242:118491. doi: https://doi.org/10.1016/j.jclepro.2019.118491.

FAOSTAT. "Commodities by country." Accessed 12 December 2019. http://www.fao.org/faostat/en/#rankings/commodities_by_country_imports.

Friel, Sharon, Alan D. Dangour, Tara Garnett, Karen Lock, Zaid Chalabi, Ian Roberts, Ainslie Butler, et al. 2009. "Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture." Review of. *The Lancet* 374 (9706):2016-25. doi: https://doi.org/10.1016/S0140-6736(09)61753-0.
Gilbert, Natasha. 2012. "One-third of our greenhouse gas emissions come from agriculture." Review of. *Nature News*.
Goldstein, Benjamin, Steffen Foss Hansen, Mickey Gjerris, Alexis Laurent, and Morten Birkved. 2016. "Ethical aspects of life cycle assessments of diets." Review of. *Food Policy* 59:139-51. doi: https://doi.org/10.1016/j.foodpol.2016.01.006.
Golini, R., A. Moretto, F. Caniato, M. Caridi, and M. Kalchschmidt. 2017. "Developing sustainability in the Italian meat supply chain: an empirical investigation." Review of. *International Journal of Production Research* 55 (4):1183-209. doi: 10.1080/00207543.2016.1234724.
Goronovski, Andrei, P James Joyce, Anna Björklund, Göran Finnveden, and Alan H Tkaczyk. 2018. "Impact assessment of enhanced exposure from Naturally Occurring Radioactive Materials (NORM) within LCA." Review of. *Journal of Cleaner Production* 172:2824-39.
Goucher, Liam, Richard Bruce, Duncan D. Cameron, S. C. Lenny Koh, and Peter Horton. 2017. "The environmental impact of fertilizer embodied in a wheat-to-bread supply chain." Review of. *Nature Plants* 3 (3):17012. doi: 10.1038/nplants.2017.12.
Grant, Wyn. 2016. "The challenges facing UK farmers from Brexit." Review of. *EuroChoices* 15 (2):11-6.
Green, Rosemary F., Edward J. M. Joy, Francesca Harris, Sutapa Agrawal, Lukasz Aleksandrowicz, Jon Hillier, Jennie I. Macdiarmid, et al. 2018. "Greenhouse gas emissions and water footprints of typical dietary patterns in India." Review of. *Science of the Total Environment* 643:1411-8. doi: https://doi.org/10.1016/j.scitotenv.2018.06.258.
Green, Rosemary, James Milner, Alan D. Dangour, Andy Haines, Zaid Chalabi, Anil Markandya, Joseph Spadaro, and Paul Wilkinson. 2015. "The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change." Review of. *Climatic Change* 129 (1):253-65. doi: 10.1007/s10584-015-1329-y.
He, P., G. Baiocchi, K. Feng, K. Hubacek, and Y. Yu. 2019. "Environmental impacts of dietary quality improvement in China." Review of. *J Environ Manage* 240:518-26. doi: 10.1016/j.jenvman.2019.03.106.
Heidari, Mohammad Davoud, Mark AJ Huijbregts, Hossein Mobli, Mahmoud Omid, Shahin Rafiee, and Rosalie van Zelm. 2017. "Regionalised life cycle assessment of pasta production in Iran: Damage to terrestrial ecosystems." Review of. *Journal of Cleaner Production* 159:141-6.
Heller, Martin C, Gregory A Keoleian, and Walter C Willett. 2013. "Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: a critical review." Review of. *Environmental Science and Technology* 47 (22):12632-47.
Hobbs, Jill E. 2020. "Food supply chains during the COVID-19 pandemic." Review of. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie* 68 (2):171-6.
Huan-Niemi, E., M. Kaljonen, M. Knuuttila, J. Niemi, and M. Saarinen. 2020. "The impacts of dietary change in Finland: food system approach." Review of. *Agricultural and Food Science* 29 (4):372-82.
Huijbregts, Mark AJ, Zoran JN Steinmann, Pieter MF Elshout, Gea Stam, Francesca Verones, Marisa Vieira, Michiel Zijp, Anne Hollander, and Rosalie van Zelm. 2017.

"ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level." Review of. *The International Journal of Life Cycle Assessment* 22 (2):138-47.
Koh, S. C. L., A. Genovese, A. A. Acquaye, P. Barratt, N. Rana, J. Kuylenstierna, and D. Gibbs. 2013. "Decarbonising product supply chains: design and development of an integrated evidence-based decision support system - the supply chain environmental analysis tool (SCEnAT)." Review of. *International Journal of Production Research* 51 (7):2092-109. doi: 10.1080/00207543.2012.705042.
Lake, Alison, Adolf Acquaye, Andrea Genovese, N Kumar, and SCL Koh. 2015. "An application of hybrid life cycle assessment as a decision support framework for green supply chains." Review of. *International Journal of Production Research* 53 (21):6495-521.
Li, H. M., T. Wu, X. Wang, and Y. Qi. 2016. "The Greenhouse Gas Footprint of China's Food System: An Analysis of Recent Trends and Future Scenarios." Review of. *Journal of Industrial Ecology* 20 (4):803-17. doi: 10.1111/jiec.12323.
Liu, Zhu, Yong Geng, Soeren Lindner, and Dabo Guan. 2012. "Uncovering China's greenhouse gas emission from regional and sectoral perspectives." Review of. *Energy* 45 (1):1059-68.
Mogale, D. G., A. Ghadge, N. Cheikhrouhou, and M. K. Tiwari. 2022. "Designing a food supply chain for enhanced social sustainability in developing countries." Review of. *International Journal of Production Research*. doi: 10.1080/00207543.2022.2078746.
Mogale, DG, Naoufel Cheikhrouhou, and Manoj Kumar Tiwari. 2020. "Modelling of sustainable food grain supply chain distribution system: a bi-objective approach." Review of. *International Journal of Production Research* 58 (18):5521-44.
Morison, JIL, and RB Matthews. 2016. "Agriculture and forestry climate change impacts summary report." Review of. *Living With Environmental Change*.
Muñoz, Ivan, Llorenç Milà i Canals, and Amadeo R Fernández-Alba. 2010. "Life cycle assessment of the average Spanish diet including human excretion." Review of. *The International Journal of Life Cycle Assessment* 15 (8):794-805.
NFS. 2021. "National Food Strategy - The Plan: Independent Review." In.
Office, Cabinet. 2008. "Food Matters: Towards a strategy for the 21st Century." Review of. *London: The Strategy Unit, Cabinet Office*.
Office of National Statistics. 2014. "About Family Food." In *Living Costs and Food Survey*.
Oliveau, S, and CZ Guilmoto. 2005. "Spatial correlation and demography Exploring India's demographic patterns' " In *XXVe Congrès International de la Population*. Tours, France.
Orr, J., and A. McCamley. 2017. "Evaluating the effectiveness of a community-based dietary intervention in Nottingham." Review of. *British Food Journal* 119 (5):1091-101. doi: 10.1108/bfj-09-2016-0444.
Parsons, Kelly. 2020. "Who makes food policy in England? -A map of government actors and activities." In. London: Centre for Food policy.
Prajapati, Dhirendra, Felix T. S. Chan, Yash Daultani, and Saurabh Pratap. 2022. "Sustainable vehicle routing of agro-food grains in the e-commerce industry." Review of. *International Journal of Production Research*:1-26. doi: 10.1080/00207543.2022.2034192.
Rashedi, A, and Taslima Khanam. 2020. "Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method." Review of. *Environmental Science Pollution Research* 27 (23):29075-90.

Reynolds, Christian J, Graham W Horgan, Stephen Whybrow, and Jennie I Macdiarmid. 2019. "Healthy and sustainable diets that meet greenhouse gas emission reduction targets and are affordable for different income groups in the UK." Review of. *Public Health Nutrition* 22 (8):1503-17.

Reza, Bahareh, Rehan Sadiq, and Kasun Hewage. 2014. "Emergy-based life cycle assessment (Em-LCA) of multi-unit and single-family residential buildings in Canada." Review of. *International Journal of Sustainable Built Environment* 3 (2):207-24. doi: 10.1016/j.ijsbe.2014.09.001.

Scarborough, P., S. Allender, D. Clarke, K. Wickramasinghe, and M. Rayner. 2012. "Modelling the health impact of environmentally sustainable dietary scenarios in the UK." Review of. *European journal of clinical nutrition* 66 (6):710-5. doi: 10.1038/ejcn.2012.34.

Scarborough, P., P. N. Appleby, A. Mizdrak, A. D. Briggs, R. C. Travis, K. E. Bradbury, and T. J. Key. 2014a. "Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK." Review of. *Clim Change* 125 (2):179-92. doi: 10.1007/s10584-014-1169-1.

Scarborough, P., A. Kaur, L. Cobiac, P. Owens, A. Parlesak, K. Sweeney, and M. Rayner. 2016. "Eatwell Guide: modelling the dietary and cost implications of incorporating new sugar and fibre guidelines." Review of. *BMJ Open* 6 (12):e013182. doi: 10.1136/bmjopen-2016-013182.

Scarborough, Peter, Paul N. Appleby, Anja Mizdrak, Adam D. M. Briggs, Ruth C. Travis, Kathryn E. Bradbury, and Timothy J. Key. 2014b. "Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK." Review of. *Climatic Change* 125 (2):179-92. doi: 10.1007/s10584-014-1169-1.

Scheelbeek, Pauline, Rosemary Green, Keren Papier, Anika Knuppel, Carmelia Alae-Carew, Angela Balkwill, Timothy J Key, Valerie Beral, and Alan D Dangour. 2020. "Health impacts and environmental footprints of diets that meet the Eatwell Guide recommendations: analyses of multiple UK studies." Review of. *BMJ Open* 10 (8):e037554.

Schuur, Gerlienke, L Preller, W ter Burg, D Kroese, J van Engelen, S Bausch-Goldbohm, H van Kranen, P Kramers, and M van Raaij. 2009. "Health impact assessment of policy measures for chemicals in non-food consumer products." In.: National Institute for Public Health and the Environment.

Semba, R. D., S. de Pee, B. Kim, S. McKenzie, K. Nachman, and M. W. Bloem. 2020. "Adoption of the 'planetary health diet' has different impacts on countries' greenhouse gas emissions." Review of. *Nature Food* 1 (8):481-4. doi: 10.1038/s43016-020-0128-4.

Shi, Kaifang, Bailang Yu, Yuyu Zhou, Yun Chen, Chengshu Yang, Zuoqi Chen, and Jianping Wu. 2019. "Spatiotemporal variations of CO2 emissions and their impact factors in China: A comparative analysis between the provincial and prefectural levels." Review of. *Applied Energy* 233-234:170-81. doi: https://doi.org/10.1016/j.apenergy.2018.10.050.

Smith, Pete. 2012. "Agricultural greenhouse gas mitigation potential globally, in E urope and in the UK: what have we learnt in the last 20 years?" Review of. *Global Change Biology* 18 (1):35-43.

Springmann, M., H. C. J. Godfray, M. Rayner, and P. Scarborough. 2016. "Analysis and valuation of the health and climate change cobenefits of dietary change." Review of. *Proceedings of the National Academy of Sciences of the United States of America* 113 (15):4146-51. doi: 10.1073/pnas.1523119113.

Stoll-Kleemann, S., and U. J. Schmidt. 2017. "Reducing meat consumption in developed and transition countries to counter climate change and biodiversity loss: a review of influence factors." Review of. *Regional Environmental Change* 17 (5):1261-77. doi: 10.1007/s10113-016-1057-5.

Temple, Norman J, and Nelia P Steyn. 2011. "The cost of a healthy diet: A South African perspective." Review of. *Nutrition* 27 (5):505-8.

Tilman, D., and M. Clark. 2014. "Global diets link environmental sustainability and human health." Review of. *Nature* 515 (7528):518-+. doi: 10.1038/nature13959.

Tom, Michelle S, Paul S Fischbeck, and Chris T Hendrickson. 2016. "Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US." Review of. *Environment Systems Decisions* 36 (1):92-103.

Tukker, Arnold, R Alexandra Goldbohm, Arjan De Koning, Marieke Verheijden, René Kleijn, Oliver Wolf, Ignacio Pérez-Domínguez, and Jose M Rueda-Cantuche. 2011. "Environmental impacts of changes to healthier diets in Europe." Review of. *Ecological Economics* 70 (10):1776-88.

van Dooren, C., C. Keuchenius, J. H. M. de Vries, J. de Boer, and H. Aiking. 2018. "Unsustainable dietary habits of specific subgroups require dedicated transition strategies: Evidence from the Netherlands." Review of. *Food Policy* 79:44-57. doi: 10.1016/j.foodpol.2018.05.002.

Vetter, Sylvia H., Tek B. Sapkota, Jon Hillier, Clare M. Stirling, Jennie I. Macdiarmid, Lukasz Aleksandrowicz, Rosemary Green, Edward J. M. Joy, Alan D. Dangour, and Pete Smith. 2017. "Greenhouse gas emissions from agricultural food production to supply Indian diets: Implications for climate change mitigation." Review of. *Agriculture, Ecosystems & Environment* 237:234-41. doi: https://doi.org/10.1016/j.agee.2016.12.024.

Vicente-Vicente, José Luis, Alexandra Doernberg, Ingo Zasada, David Ludlow, Damian Staszek, Joanna Bushell, Ali Hainoun, Wolfgang Loibl, and Annette Piorr. 2021. "Exploring alternative pathways toward more sustainable regional food systems by foodshed assessment – City region examples from Vienna and Bristol." Review of. *Environmental Science & Policy* 124:401-12. doi: https://doi.org/10.1016/j.envsci.2021.07.013.

von Philipsborn, Peter, Jan M. Stratil, Jacob Burns, Laura K. Busert, Lisa M. Pfadenhauer, Stephanie Polus, Christina Holzapfel, Hans Hauner, and Eva Rehfuess. 2019. "Environmental interventions to reduce the consumption of sugar-sweetened beverages and their effects on health." Review of. *The Cochrane database of systematic reviews* 6 (6):CD012292-CD. doi: 10.1002/14651858.CD012292.pub2.

Weidema, Bo P 2015. "Comparing three life cycle impact assessment methods from an endpoint perspective." Review of. *Journal of Industrial Ecology* 19 (1):20-6.

Willett, Walter, Johan Rockström, Brent Loken, Marco Springmann, Tim Lang, Sonja Vermeulen, Tara Garnett, David Tilman, Fabrice DeClerck, and Amanda Wood. 2019. "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems." Review of. *The Lancet* 393 (10170):447-92.

Wrigley, Neil. 2002. "'Food deserts' in British cities: policy context and research priorities." Review of. *Urban studies* 39 (11):2029-40.

Yakovleva, Natalia, Joseph Sarkis, and Thomas Sloan. 2012. "Sustainable benchmarking of supply chains: the case of the food industry." Review of. *International Journal of Production Research* 50 (5):1297-317.

Zhu, Z. G., F. Chu, A. Dolgui, C. B. Chu, W. Zhou, and S. Piramuthu. 2018a. "Recent advances and opportunities in sustainable food supply chain: a model-oriented

review." Review of. *International Journal of Production Research* 56 (17):5700-22. doi: 10.1080/00207543.2018.1425014.
Zhu, Zhanguo, Feng Chu, Alexandre Dolgui, Chengbin Chu, Wei Zhou, and Selwyn Piramuthu. 2018b. "Recent advances and opportunities in sustainable food supply chain: a model-oriented review." Review of. *International Journal of Production Research* 56 (17):5700-22.

Figure Captions and Alt Text

Figure 1 Caption: Change in imports to UK from EU and RoW between 2000 and 2018.
Figure 1 Alt Text: Figure showing 12 small line charts depicting the import of twelve different food commodities from the EU and Rest of the World (RoW) to the UK between the years 2000 and 2018.

Figure 2a Caption: Change in per capita weekly GHG emissions in English regions resulting from a change in diet patterns to those based on UK Eatwell recommendations. Decimal places could not be shown due to font size limitations.
Figure 2a Alt Text: Figure shows a ribbon chart displaying Greenhouse gas emissions between the years 2000 and 2018. The figure shows eight colored ribbons stacked together, corresponding to the difference between emissions in a UK Eat well scenario and a Business As Usual scenario from the 8 English regions.

Figure 2b Caption: Change in per capita weekly GHG emissions in UK nations resulting from a change in diet patterns to those based on UK Eatwell recommendations. Decimal places could not be shown due to font size limitations.
Figure 2b Alt Text: Its a ribbon chart displaying Greenhouse gas emissions between the years 2000 and 2018. The figure shows four colored ribbons stacked together, corresponding to the difference between emissions in a UK Eat well scenario and a Business As Usual scenario from the four nations that comprise the United Kingdom.

Figure 3 Caption: Local auto-correlations for emissions from UK nations (Scotland, Wales and Northern Ireland) and English regions between 2001 and 2018. Areas shaded dark green show correlations with greater statistical significance using Bonferroni criterion.

Figure 3 Alt Text: Figure displays seven maps of the United Kingdom correponding to different years when a significant correlation for emissions was discovered. Map areas with grey color shows no correlation, those with light green shading indicate significant correlations at 95% confidence interval and those highlighted dark green indicate significant correlations at 99% confidence interval.

Figure 4a Caption: Variation in per capita weekly expenditure per person per week in £s in English regions.
Figure 4a Alt Text: Figure shows horizontal bar charts stacked side by side for the eight English regions corresponding to the period between the years 2000 and 2018.

Figure 4b Caption: Variation in per capita weekly expenditure per person per week in £s in UK nations.
Figure 4b Alt Text: Figure shows horizontal bar charts stacked side by side for the four UK nations corresponding to the period between the years 2000 and 2018.

Figure 5a Caption: Reduction in health impacts of GHG emissions in DALYs per million people for English regions and UK nations.
Figure 5a Alt Text: Figure shows two surface charts for Disability Adjusted Life Years between the years 2000 and 2018. The chart above is for the four UK nations while the one below is for the eight English regions.

Figure 5b Caption: Reduction in terrestrial ecosystem impacts of GHG emissions in life-years per million species for English regions and UK nations.
Figure 5b Alt Text: Figure shows two surface charts for impacts on terrestrial species between the years 2000 and 2018. The chart above is for the four UK nations while the one below is for the eight English regions.

Figure 5c Caption: Reduction in aquatic ecosystem impacts of GHG emissions in life-years per billion species for English regions and UK nations.
Figure 5c Alt Text: Figure shows two surface charts for impacts on aquatic species between the years 2000 and 2018. The chart above is for the four UK nations while the one below is for the eight English regions.