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The future of meat and dairy consumption in the UK: exploring different policy scenarios to meet net zero targets and improve population health

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ABSTRACT

1. Non-Technical Summary

To meet the UK's greenhouse gas (GHG) emissions targets, the Climate Change Committee (CCC) recommended to reduce current meat and dairy intake by 20% by 2030. In this study, we modelled the impact of potential dietary changes on GHG emissions and water use with the selected scenarios based on the trend of food purchase and meat and dairy reduction policy. We show that implementing fiscal measures and facilitating innovations in production of meat alternatives would accelerate existing positive trends, help the UK reach the CCC 2030 target of 20% meat and dairy reduction and increase fruit and vegetable intake.

2. Technical Summary

We used 2001-2019 data from the Family Food module of the Living Costs and Food Survey (LCF), an annual UK survey of about 5,000 representative households recording quantities of all food and drink purchases, to model four 2030 dietary scenarios: Business as usual (BAU); two fiscal policy scenarios ('fiscal 10%' and 'fiscal 20%'), combining either a 10% meat and dairy tax and a 10% fruit and vegetable subsidy, or a 20% tax and 20% subsidy on the same foods; and an 'innovation scenario' substituting traditionally-produced meat and dairy with plant-based analogues and animal proteins produced in laboratories. Compared to 2019 levels, we forecasted reductions in the range of 5-30% for meat and 8-32% for dairy across scenarios. Meat reductions could be up to 21.5% (fiscal20%) and 30.4% (innovation). For all scenarios we forecasted an increase in fruit and vegetables intake in the range of 3-13.5%; with the fiscal 20% scenario showing highest increases (13.5%). GHG emissions and water use reductions were highest for the innovation scenario (-19.8%, -16.2%) followed by fiscal 20% (-15.8%, -9.2%) fiscal 10% (-12.1%, 5.9%) and BAU (-8.3%, -2.6%) scenarios. Compared to average households, low-income households had similar patterns of change, but both past and predicted purchase of meat, fruit and vegetables and environmental footprints were lower.

Social Media Summary

Meat and dairy-reduction policies would help meet net zero targets and improve population health in the UK.

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Introduction

Following recommendations from the Committee on Climate Change (CCC) (CCC, 2019), the UK Government has committed to reduce greenhouse gas (GHG) emissions by 78% by 2035 compared to 1990 levels and to 'net zero' by 2050 (UK Government, 2020). To reach this ambitious goal it will be necessary to act on multiple technologies and behaviours through well-designed policies that involve many systems.

Recent research has indicated that it may not be possible to meet carbon reduction targets without substantial reductions in emissions from our food systems (Clark *et al*., 2020). It has been estimated that globally the food system, from production to consumption, is responsible for a third of all GHG emissions, with land use and agriculture representing the largest contribution (Crippa *et al.,* 2021). In the UK the agriculture sector accounted for 10% of total GHG emissions in 2019 (Department for Business, Energy & Industrial Strategy, 2021), but this figure includes only UK production and transport, and does not factor in GHG emissions from food imports or land use change. Given that the UK imports a large proportion of its food (the official estimate of 45% imports (Defra, 2022a) is likely to be a considerable underestimate given that it does not account for imports of ingredients for processed foods), it is likely to be more appropriate to try to reduce the total GHG emissions from UK dietary consumption rather than production.

One of the key recommendations of the CCC sixth carbon budget is to reduce current meat and dairy intake by 20% by 2030 (CCC, 2019). Compared to plant-based products, animal products have on average greater GHG emissions per unit weight (Audsley *et al.*, 2009). Livestock production requires high amounts of natural resources, such as land for grazing and feed production leading to deforestation and land clearing. Methane production caused by enteric fermentation in ruminants' digestive systems and nitrous oxide from manure storage and fertilizers are also responsible for meat's high GHG impact, as methane and nitrous oxide have a much higher global warming potential than carbon dioxide (Grossi *et al.*, 2019; FAO, 2017). A shift towards plant-based diets, rich in fruit and vegetables, nuts and wholegrains would also reduce the risk of mortality and chronic disease morbidity, including cardiovascular disease and type 2 diabetes (Kim *et al.*, 2019; Anne *et al*., 2019,; Afshin *et al.*, 2014). Transforming food systems to make them more sustainable while providing healthier foods has become an urgent priority, which will require multiple policies (Willett *et al*., 2019).

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By some measures, diets in the UK are becoming healthier. Consumption of red and processed meat, which has been associated with increased risk of total cancer and cardiovascular mortality (Wang *et al.*, 2016) has declined in all age groups since 2008 although much of this has been replaced by increasing poultry consumption (PHE, 2020a). However, dietary risk factors are still the fourth largest cause of death and disability in the UK, only exceeded by high glucose levels, high body mass index (both also highly correlated with diet) and tobacco consumption (GBD, 2019). Fruit and vegetable intake remains low; only 33% of adults and 12% of children aged 11-18 years meet the 5-a-day target (PHE, 2020a) recommended by the Eatwell Guide (Food Standards Agency, 2020). Across all age and sex groups, people with lower incomes have significantly lower fruit and vegetable intake, with consumption increasing by up to 4% for every £10,000 increase in household equivalised income (PHE, 2020b). People from more deprived communities are also more likely to be obese than those from more affluent areas, and this gap has widened in recent years (NHS digital, 2020). Therefore, policies affecting healthy food intake patterns at the population level could have a significant impact on low income families.

A recent study using a large sample of more than 500,000 British participants showed that only 0.1% adhered to all 9 Eatwell Guide recommendations (Scheelbeek *et al.*, 2020a). The same study also suggested that increasing adherence to the red and processed meat recommendations would have the greatest positive environmental impact of all dietary changes.

There is thus an urgent need to implement policies that help accelerate existing positive trends in reduction of meat consumption while facilitating a shift towards healthier and more sustainable diets, with lower GHGs and water footprints. The recently published Government Food Strategy articulated some key priorities for action, including boosting fruit and vegetable production, supporting alternative protein research and innovation and cutting obesity levels (Defra, 2022b). The aim of this study was to model the impact of dietary and policy scenarios designed to reduce intake of animal-source foods on UK consumption of meat, dairy, fruit and vegetables. To this end, we model four future dietary scenarios to 2030: one scenario based on recent purchase trends and three meat and dairy reduction policy-based scenarios. The objectives of the analyses are to evaluate: 1) how far each scenario would go towards reaching the 2030 CCC 20% reduction target for consumption of meat and dairy; 2) how each scenario would impact intake of fruit and vegetables; 3) the environmental impacts of each scenario, including GHG emissions and water footprint using published life-cycle analyses; 4) the extent to which each scenario would meet the Eatwell Guide recommendations on fruit and vegetable and red and processed meat consumption. To our knowledge this is the first study to assess the potential of food policies to reach the CCC meat and dairy reduction targets and to model reductions in conventionally produced animal foods under a scenario of high innovation involving substitution of meat and dairy with plant-based alternatives.

Methods

Dietary data

Dietary data were taken from the Family Food module of the Living Costs and Food Survey (LCF) (Defra, 2020c). In brief, the LCF is an annual survey of about 5,000 households in the UK. The Family Food module records quantities of all food and drink purchases. Purchases are self-reported using a 2-week diary supplemented by till receipts of all purchases including eating out. Although estimated intakes are per person, the unit of measurement is the household, and it is not possible to know who in the household consumed what. Therefore, further disaggregation by age and sex might have resulted in inaccurate estimates and was not pursued.

For this study we used annual summary time series data of average estimated consumption per person from 2001/2002, the first year of the Family Food module, to 2018/19. For each year, we aggregated 228 food items into 19 food and drink groups: cereals, vegetable oils, fruit, vegetables, pulses, potatoes, nuts and seeds, foods high in fat sugar and salt (HFSS), dairy, eggs, beef, lamb, pork, poultry, fish, dairy and meat alternatives (DMA), soft drinks, alcoholic drinks, coffee, tea, and cocoa drinks. Only fresh, canned, frozen and dried fruit and vegetables were included in the fruit and vegetables category because of their nutritional value being different from processed vegetable foods, which are often high in salt. Fruit and vegetables in processed foods, such as soups and sauces, and fruit juices were not included. Meat and dairy alternatives included non-dairy milks, soy and other novel protein foods. Processed meat and meat in composite dishes were disaggregated and incorporated into the four meat production categories. Dairy products included milk, yogurt, cheese, cream and butter. All foods were expressed as grams per person per day. Estimated consumption was calculated for the UK as a whole and for the lowest quintile of equivalised household income, a measure of income that takes into account the size and composition of the household (Defra, 2020c).

Scenario models

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Starting from repeated surveys of food consumption using the LCF dietary data as explained above, we constructed three broad future scenarios of how dietary intakes might be in 2030 in the UK. The three broad scenarios modelled are: 1) Business as usual (BAU) scenario; 2) Fiscal policy scenarios (including 'Fiscal 10%' and "fiscal 20%"); and 3) Innovation scenario assuming that some meat and dairy would be replaced with plant-based alternatives. For all scenarios a different set of assumptions and data were used to make evidence-based projections. More details about these are given below and in the Appendix. To quantify the uncertainties around these estimates we conducted a Monte Carlo simulation. We then calculated how each 2030 scenario would impact GHG and water footprints and compared these with 2019 levels. Finally, we evaluated the extent to which each scenario met the recommendations for fruit and vegetables, red and processed meat consumption in the Eatwell Guide as a measure of healthy eating impact.

1. <u>BAU scenario</u>

Based on past trends from 2001 to 2019, we forecasted the UK dietary trajectories for each of 19 food and drink groups from 2020 to 2030 in the absence of any new policy intervention by fitting a range of autoregressive integrated moving average (ARIMA) (Newbold, 1983, Praveen *et al.*, 2020; Sahai *et al.*, 2020) models as well as linear regression models. The final model was selected according to Bayesian Information Criteria and the Akaike's Information Criteria. The ARIMA (0,1,0) performed best for most foods and was used for all food groups. This model incorporates one level of differentiation, I(1) and no autoregressive AR(0), or moving average MA(0) elements, making it equivalent to a random walk model.

2. <u>Fiscal scenarios</u>

We modelled two fiscal scenarios that combined a meat and dairy tax and a fruit and vegetable subsidy. These scenarios propose an increase in the price of all meat and dairy to account for their environmental, climate, biodiversity and health costs (Cedelft, 2020) and an equivalent decrease in the price of fruit and vegetables. The first introduces a 20% tax on meat and dairy and a 20% subsidy on fruit and vegetables ('Fiscal 20%'). A subsidy of 20% was recommended by WHO (WHO, 2015) based on strong evidence that subsidies for fresh fruits and vegetables that reduce prices by 10–30% are effective in increasing fruit and vegetable consumption. There is also evidence that taxes higher than 20% on beverages and foods are more likely to positively impact health behaviours compared to lower tax rates (Wright *et al.*, 2017). However, real-world taxes have been mostly set at a lower value. For example, a

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review of sugar sweetened beverages (SSB) taxes indicated that out of 12 SSB taxes, only 2 were above 20% with the majority being around 5% (Teng *et al.*, 2019). Therefore, we modelled a second fiscal model with more realistic fixed tax and subsidy rates of 10% ('Fiscal 10%'). Food purchase in 2030 according to the BAU scenario was used as the baseline to which the fiscal scenario was applied. To calculate the change in meat, dairy and fruit and vegetable purchase as a consequence of changed prices, we used UK-specific price elasticities estimated by Defra using 2009 Family Food data (Tiffin *et al.*, 2011). Further details of the type of price elasticities and the formula used are given in the **Appendix**.

3. Innovation scenario

The innovation scenario models the substitution of traditionally produced meat and dairy with more sustainable alternatives: plant-based meat (meat analogues) and dairy and animal proteins produced in laboratories (cultured meat or precision fermentation). To estimate the amount of farmed animal meat that would be substituted with either meat analogues or cultured meat we used estimates of market share from published discrete choice experiment studies (van Loo *et al.*, 2020; Slade *et al.*, 2018). These studies collect data on individual choices over different hypothetical alternatives to estimate the potential market share of plant-based meat analogues and laboratory produced animal protein if these were comparable in price and taste to farmed animal meat. We multiplied BAU 2030 consumption by the proportional reduction in meat and dairy according to the market share reported in the discrete choice experiments; to aid accuracy, we excluded those who already do not consume meat and dairy proteins. We assumed that meat and dairy will be substituted with the ingredients making up meat and dairy alternatives according to current market availability and future predictions. Further details about the innovation model method are given in the **Appendix**.

All scenario analyses were conducted using the statistical software Stata 17.

Uncertainty analyses

We conducted Monte Carlo simulation to quantify uncertainties around these estimates. Input parameters for BAU estimates were obtained from ARIMA forecasted standard errors. As no error measures were available for the price elasticities calculated from Defra, we used the average variability for own and cross price elasticities from a recent paper that used home-scan data to calculate

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elasticities for purchases in Great Britain (Cornelsen *et al.*, 2019). For the innovation scenario we assumed an average 20% variability around market shares as no error estimate was available for these parameters. All input parameters were assumed to be normally distributed. The simulation model was implemented in MS Excel and each scenario was run 10,000 times.

GHG and water footprint

We calculated GHG emissions and water use for the whole diet per person per day for baseline and all scenarios using values adapted from Poore and Nemecek's 2018 systematic review of global environmental footprints (Poor and Nemecek, 2018). We aggregated the Family Food data into 54 food groups to map these to the foods in the review and then aggregated the footprints further into the 19 groups used for the rest of the analysis on the basis of weighted average consumption, so that footprints could be assigned relatively accurately. For meat we calculated the weighted meat content of process meat and applied GHG accordingly. The 54 food groups and their environmental footprints are shown in **table S2**. GHG emissions were aggregated into global warming potential in CO_2 equivalents using IPCC (2013) characterisation factors with climate-carbon feedbacks. Water use (WU) was calculated as the freshwater withdrawals related to food consumption, which includes irrigation water, animal drinking water, and water used during food processing. To calculate the correct impact of each food we included information on whether the food was imported or produced in the UK and used location-specific GHG footprints and water use where available. The following equation was used to allocate GHG and water footprint values depending on the imported amount:

$$I_f = (Consumption) * (1\text{-}Import) * National\ I) + (Consumption * Import * Global\ I)$$

Where: *I* = impact (GHG in kgCO2eq/kg; WU in L/per kg); *f*=food group; Consumption is kg/d pp; *Imports* are percentage of imported food; Global refers to average emissions across all countries for which an estimate is provided excluding UK.

Adherence to Eatwell Guide recommendations

We chose the Eatwell Guide recommendations as measures of healthy eating impact of the policy scenarios. Although not many people achieve most of the recommendations, the Guide is a policy-relevant tool to define balanced healthy diets and is the acknowledged UK government target. We evaluated the extent to which each scenario met the following two Eatwell Guide recommendations: a)

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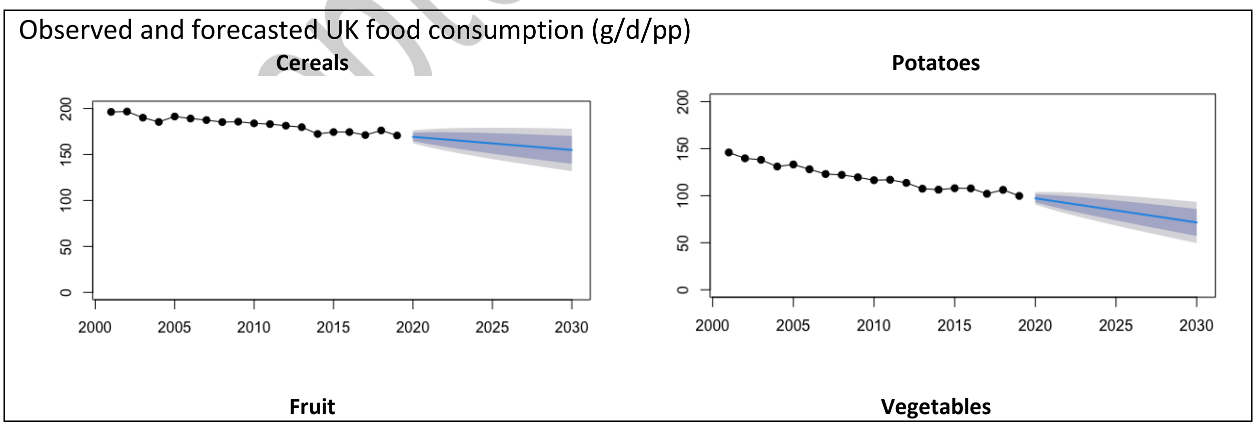
fruit and vegetables intake to be at least 400g/d equivalent to 5 portions a day; this includes fresh, canned, dried and frozen fruit and vegetables, 1 portion of pulses and maximum 150ml of pure fruit juice or smoothies; b) no more than 70g/d of red and processed meat; red meat includes beef, lamb and pork; processed meat includes meat that has been preserved by smoking, curing, salting or adding preservatives, such as sausages, bacon, ham and salami. These recommendations were chosen because of their relevance to both health and environmental outcomes and because this paper focuses on meat reduction policies with an emphasis on replacement with fruit and vegetables.

Results

Current and BAU scenario to 2030

Figure 1 shows past and forecast BAU trends in intakes of selected foods in the UK in the absence of any policy changes. In 2001-2019, we observed a decreasing trend in purchase of starchy foods (cereals -13.1%, potatoes -31.6%), vegetable oils (-7.1%), pulses (-5%), HFSS (-6.5%), dairy (-11.7), red meat (beef -17.2%, lamb -33.2%, pork -9.3%), and an increase in fruit (+6.9%), vegetables (+4.7%), nuts and seeds (+82.5%), poultry (+7.2%) eggs (+21.9%) and DMA (+169%). Based on these trends, our forecast model for 2030 compared with 2019 (**Table 1**) suggested a continuing decrease in red meat (-10.9%) and dairy (-8.1%) purchase and increase in fruit (+4%), vegetables (+2.8%), nuts and seeds (+27.6%), poultry (+4.1%), eggs (11%) and DMA (+57.7%) purchases. Trends for vegetable oils, fish, soft drinks, alcoholic drinks, tea and coffee are reported in the Appendix in **Figure S1**.



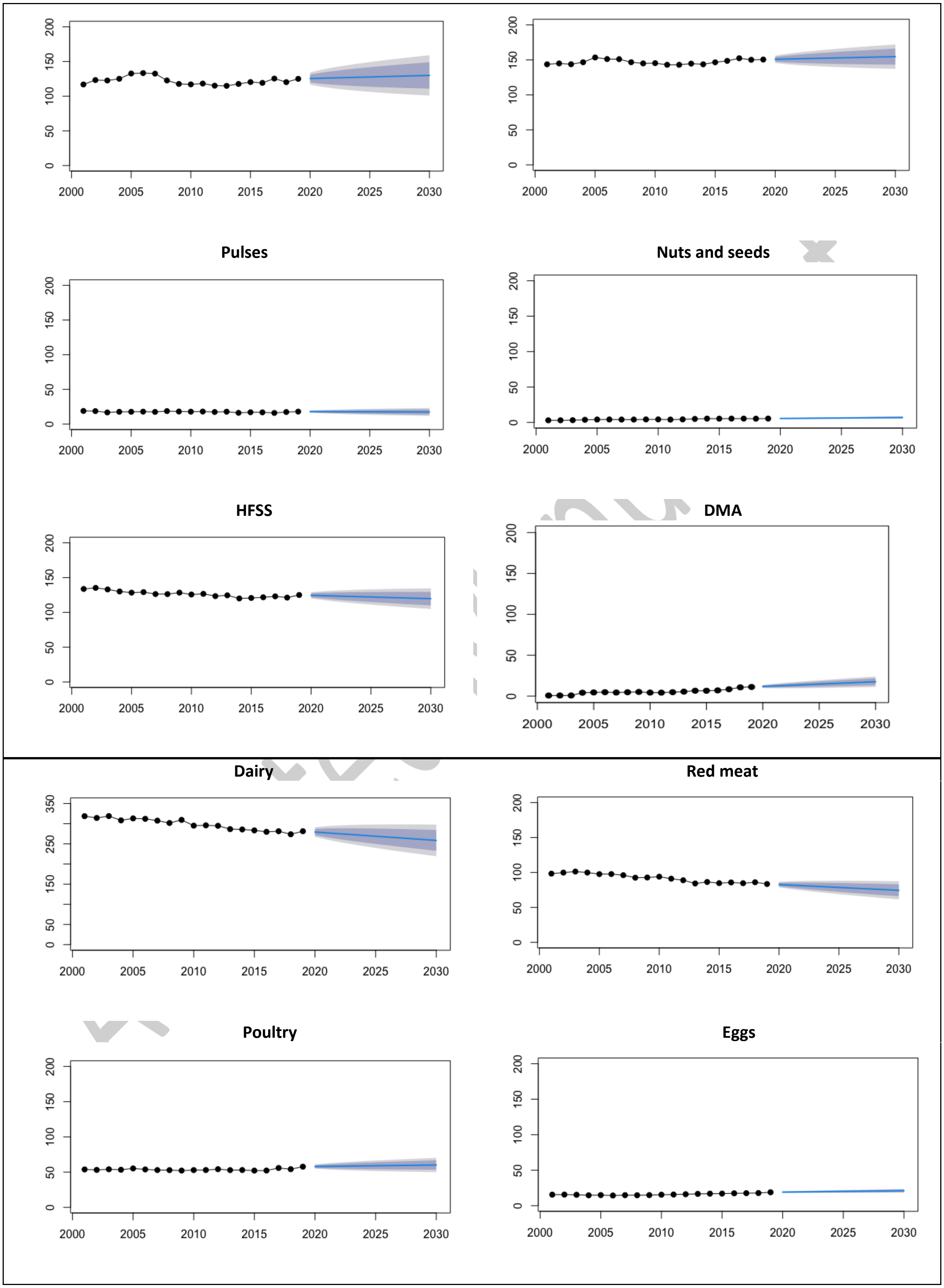


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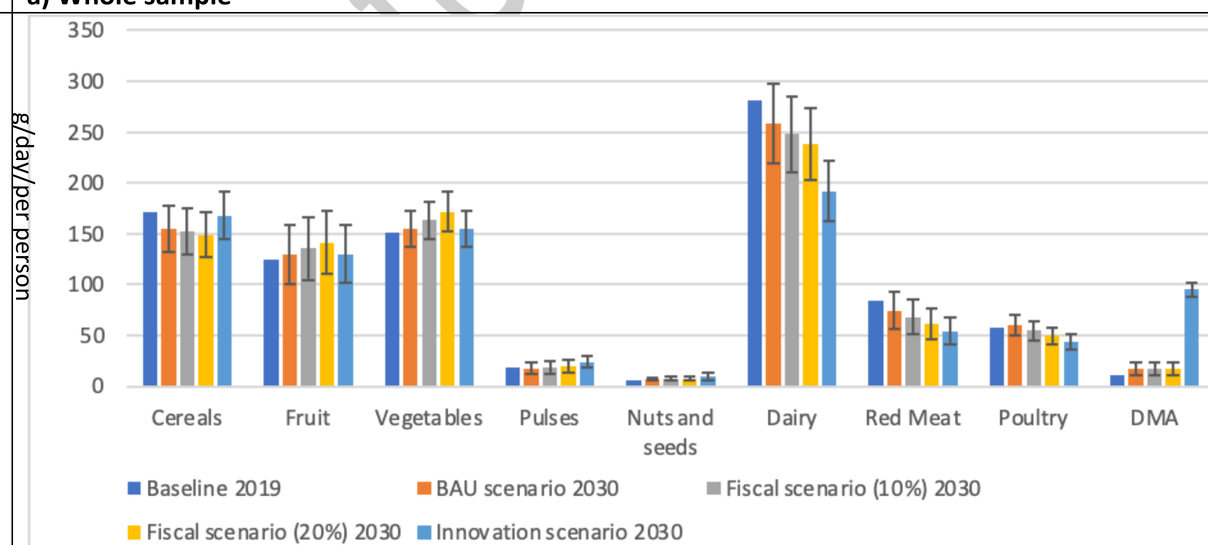
Figure 1. Trajectories of past and predicted business as usual (BAU) estimated consumption of selected foods in the UK. X axis shows year and Y axis shows estimated consumption in grams per person per day. HFSS= Foods high in fat, sugar and salt. DMA= Dairy and meat alternatives

Trends in past and predicted intakes of selected foods and drinks for the lowest quintile (low-income) of equivalised household income compared to the whole sample are shown in **Figure S3**. In 2019 low-income families consumed less fruit, vegetables, red meat, poultry and alcohol and more dairy and soft drinks compared to the whole population. When looking at the predicted changes between 2019 and 2030, low-income families showed similar trends in decreased consumption of pulses, HFSS, red meat, fish and alcoholic drinks, but different patterns for poultry (decrease for low-income and increase for the whole population) and soft drinks (increase for low-income and decrease for the whole population).

Policy Scenarios

Figure 2 shows reported purchase of meat, dairy, fruit, vegetables, cereals, pulses, nuts and seeds, and DMA for 2019 and predicted consumption of the same food groups for the four 2030 scenarios (BAU, fiscal 10%, fiscal 20%, innovation) for the whole sample (Figure 2a) and for the sub sample of low-income households (Figure 2b).

a) Whole sample



b) Low-income

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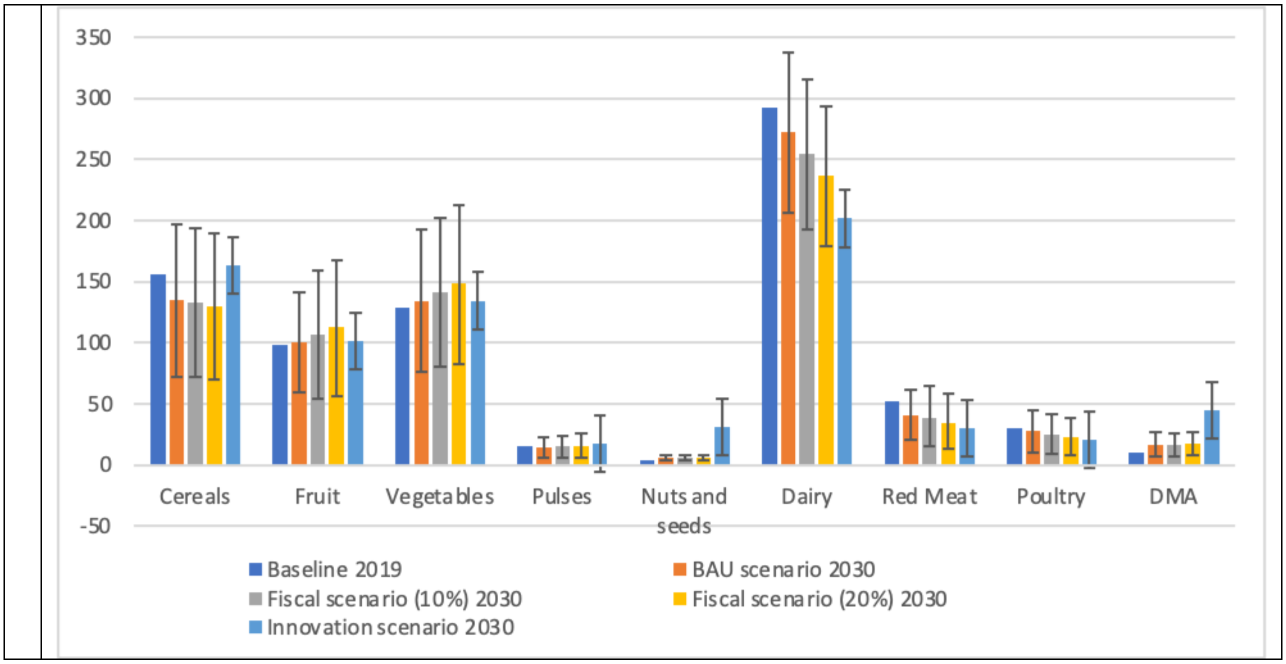

Figure 2. Comparison between current (2019) and 2030 scenarios (business as usual, innovation and fiscal scenarios) for UK food and drink purchases among a) the whole sample and b) low-income households. Estimated intakes expressed in grams per person per day. Caps are 95% confidence intervals. DMA= Dairy and meat alternatives

Table 1. Percentage change in intake for the whole sample compared to 2019 by food group in each scenario

	Scenarios			
	BAU	**Fiscal 10%**	**Fiscal 20%**	**Innovation**
Food groups	% Change (95% CI)	% Change (95% CI)	% Change (95% CI)	% Change (95% CI)
Cereals	-9.2 (-22.7, 4.3)	-11 (-25.6, 0.6)	-12.8 (-24.1, 2.3)	-1.7 (-4.1, 23)
Fruit	4 (-19.3, 27.2)	8.4 (-12, 38.1)	12.9 (-16.2, 32.8)	4 (-19.1, 27.1)
Vegetables	2.8 (-8.8, 14.3)	8.4 (1, 26.9)	14 (-3.8, 20.6)	2.8 (-8.9, 14.3)
Pulses	-3.2 (-35.2, 28.8)	2.1 (-28.3, 43)	7.4 (-31.7, 36.2)	33.5 (1.4, 65.8)
Nuts and seeds	27.6 (-1.6, 56.9)	33.1 (6.9, 70.9)	38.6 (2.3, 64.1)	76 (47, 111.4)
Dairy	-8.1 (-22.1, 5.9)	-11.7 (-28, -2.6)	-15.4 (-25.1, 1.3)	-32 (-42.3, -21.4)
Red meat	-10.9 (-32.5, 11.5)	-18.7 (-44.6, -8.4)	-26.5 (-38, 1.5)	-34.9 (-50.8, -18.7)
Poultry	4.1 (-13.4, 21.7)	-5 (-28.9, 0.6)	-14.1 (-21.2, 11)	-23.9 (-36.5, -11.3)
DMA	57.7 (0.1, 114.8)	57.4 (0.7, 115.2)	57.5 (-0.1, 115)	752 (277, 408)

DMA=Dairy and meat alternatives

Table 1 shows the percentage change in intake for selected food groups compared to 2019 levels for all scenarios for the whole sample. All three alternative policy scenarios indicated on average a greater reduction in meat and dairy consumption compared to baseline than the BAU scenario. A 10% tax on

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meat and dairy would reach the CCC target of 20% reduction in consumption of red meat only among low-income households and would not meet the target for reduction of poultry or dairy. The 20% fiscal scenario would reach an overall 19% reduction in meat and dairy for the average household (almost meeting the CCC target) and a 26% decrease for low-income households. The 20% fiscal scenario would also achieve the highest increase in purchases of fruit (13% and 14% increase compared to baseline for average and low-income households) and vegetables (14% and 15% increase for average and low-income households) by 2030. The innovation scenario was estimated to achieve the largest reduction in consumption of red meat (-35% and -42% for low-income), poultry (-24% and -33% for low-income), and dairy (-32% and -30% for low-income), and would exceed the CCC target. Purchases of pulses, nuts and seeds and cereals would be higher for the innovation scenario compared to the fiscal and BAU scenarios, as these would be the main ingredients of meat and dairy analogues. Under the innovation scenario, meat and dairy alternatives, particularly soy-based, would see an increase of 441% compared to BAU. Other food groups would not be significantly affected in our scenario models, apart from alcohol, which increased in the fiscal scenario as a consequence of higher spending availability due to the fruit and vegetable subsidies (**Figure S2).**

Estimates for the whole sample had smaller uncertainty ranges than for the low income sample, reflecting the smaller sample and less accurate estimates of purchase in the low-income sample.

GHG and water footprint

For all policy scenarios, environmental footprints of the whole diet were predicted to be lower compared to baseline and BAU levels (**Figure 3**). On average, compared to baseline, GHG emissions are predicted to be 8.3%, 12%, 15.8% and 19.8% lower for respectively the BAU, fiscal 10%, fiscal 20% and innovation scenarios. For low income families, GHG emissions are predicted to be 7.2%, 10.4%, 13.7% and 15.8% lower compared to baseline levels. Water use is also predicted to be lower for all policy scenarios compared to baseline and BAU. For the average household, water use is predicted to be 2.6%, 5.9%, 9.2%, 16.2% lower compared to baseline for respectivly the BAU, fiscal 10%, fiscal 20% and innovation scenarios. Low income households' water use is expected to increase by 1.1% for BAU compared to baseline, but to decrease by 2.8%, 6.8% and 11.9% for the fiscal 10%, fiscal 20% and innovation scenarios.

GHG emissions from food consumption were on average higher for the whole sample than for low-income households. In 2019 the average houeshold produced an estimated 5.19 kgCO_2eq/year/pp compared to 3.67 kgCO_2eq/year/pp for low-income households. Similarly, average water use from the

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diet was 557L/d/pp for the whole sample compared to 444.7L/d/pp for the low income sample. For all estimates uncertainties were wide.

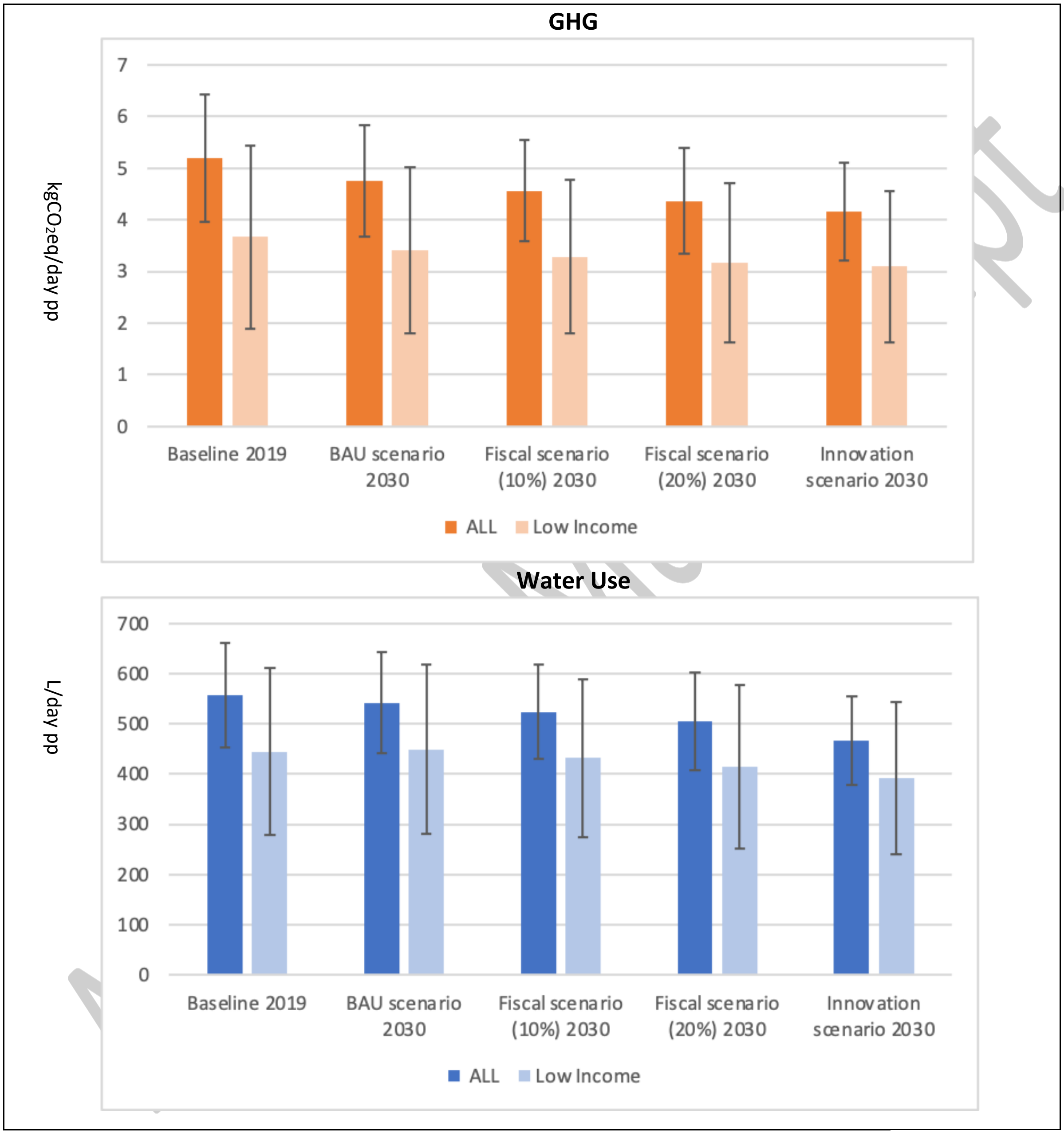

Figure 3. GHG Emissions ($kgCO_2eq$/day pp) and water use (L/d pp) of the whole diet for 2019 and for different 2030 scenarios (business as usual, innovation and fiscal scenarios) for the whole sample (blue bar) and the sub sample of low-income families (orange bar). Caps are 95% confidence intervals.

Eatwell Guide recommendations

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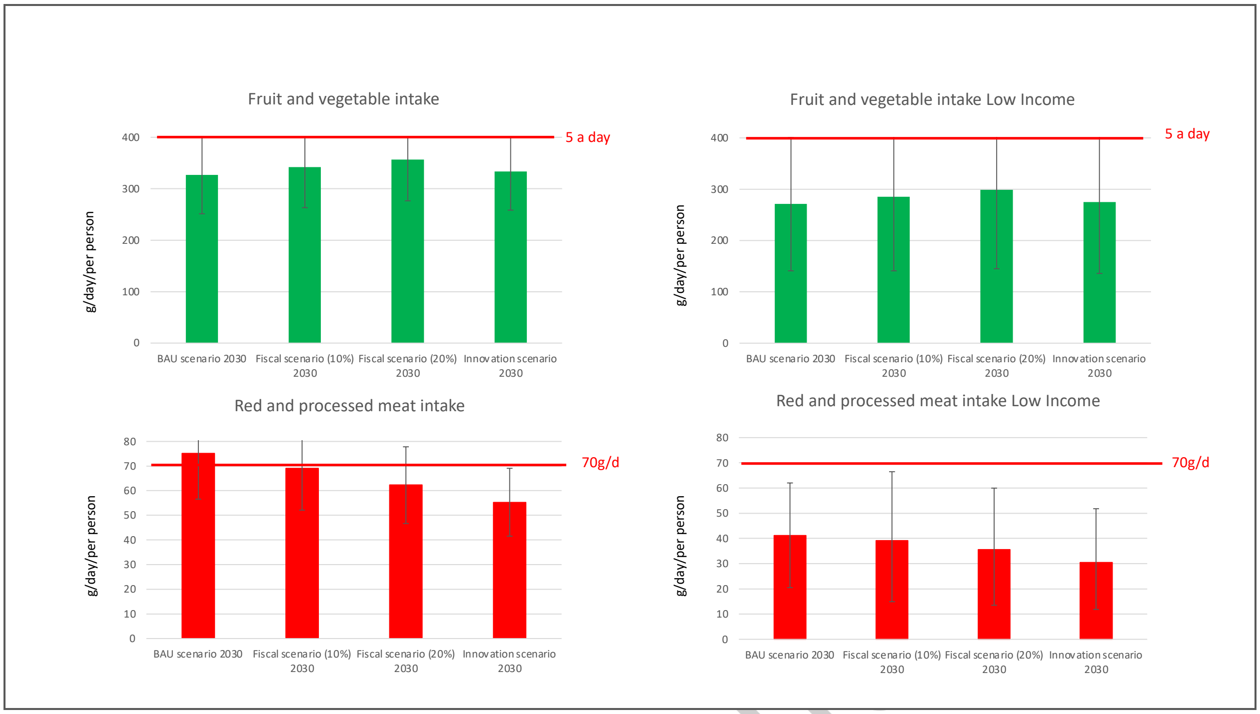

Figure 4. Extent to which the different 2030 scenarios (business as usual, innovation and fiscal scenarios) will achieve Eatwell Guide recommendations on fruit and vegetables (5-a-day; ≥400g/d) and red and processed meat (<70g/d) for the whole sample (left hand) and the sub sample of low-income families (right hand)

Figure 4 shows the extent to which each scenario would achieve the Eatwell Guide recommendations on intake of fruit and vegetables (≥400g/d) and red and processed meat (<70g/d). None of the scenarios would result in average consumption meeting the fruit and vegetable recommendation, with the highest average intake reached by the 20% tax scenario (4.5 portions per day for the whole sample and 3.7 portions per day for low-income families) and the lowest by the BAU scenario (4.1 portions per day for the whole sample and 3.4 portions per day for low-income families). Except for the BAU in the whole sample, all scenarios would achieve the recommendation on red and processed meat. The innovation scenario would limit intake to 55g/d and 31g/d respectively for the whole sample and the low-income group, while taxes and subsidies of 20% would limit intake to 62g/d and 34g/d.

Discussion

Our study shows that realistic policies to reduce consumption of animal products in the UK would accelerate existing consumption trends, help the UK reach the CCC 2030 target of 20% meat and dairy reduction and increase fruit and vegetable intake. In this study we add new evidence about which policy

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actions could be most effective at shifting UK diets towards these healthier food patterns and achieving GHG reduction targets. Our models revealed that making meat and dairy alternatives affordable and acceptable to consumers in terms of taste could lead to greater behaviour change, lower GHG emissions and lower water use than applying fiscal disincentives. However, policies that subsidise fruit and vegetables would lead to a greater increase in their purchase compared with an innovation scenario where animal food is substituted with either plant-based analogues (which are largely cereal and soya-based) or laboratory produced animal foods. It should be noted that all models had wide uncertainties, reflecting the difficulties in estimating future scenarios based on several assumptions. The results should be interpreted as indications of what might be possible with different policies. Although predicting uncertainties based on assumptions can be challenging, it is important to include these when giving future estimates.

Previous studies have shown that both largely plant-based diets and diets that meet dietary recommendations, such as the Eatwell Guide, have lower environmental footprints than average diets (Scheelbeek *et al.*, 2020; Milner *et al.*, 2015; Cobiac *et al.*, 2019). Although UK consumption of meat and dairy is already decreasing, our projections indicate that if maintained to 2030 this trend will not be enough to meet the CCC target. However, both the 20% fiscal scenario and the innovation scenario we modelled would achieve the CCC target. The recently published National Food Strategy review (National Food Strategy, 2022) recommended a 30% reduction in meat by 2032 compared to 2019 if the 5th Carbon budget and the 30x30 nature commitment to protect at least 30 percent of all lands, rivers, lakes, wetlands and Oceans by 2030 proposed by the Natural Resources Defense Council (NRDC) (NRDC, 2021) were to be achieved. Only the innovation scenario in our modelling study would achieve the Food Strategy target by 2030. All scenarios in our study would fall short of the Food Strategy recommendation to increase fruit and vegetable intake by 30%, which would bring the UK in line with the Eatwell Guide recommended 5 portions a day. Our findings show that subsidies of at least 20% might be necessary alongside innovation strategies to increase fruit and vegetable intake. But even these are unlikely to be enough, especially among low-income households.

Our study showed that a tax on meat and dairy of up to 20% would lead to a decrease in meat and dairy consumption of 21% and 15% respectively compared to 2019 levels and a decrease of 20% in fruit and vegetable prices would lead to an increase in consumption of 13.5%. GHG emissions from diets would be decreased by 15.8% under this scenario. This level of change in demand is comparable to other

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studies modelling the effect of price changes of meat and fruit and vegetables on dietary consumption. In a modelling study in the Netherlands (Broeks *et al.*, 2020) the predicted reductions in consumption following a meat tax of either 15% or 30% were 8% and 15% and the predicted fruit and vegetable increase following a 10% subsidy was 4%. A UK study (30) based on home-scan purchases estimated an increased energy purchases derived from vegetables and fruits of about 17% and 15% from a 20% price decrease. A New Zealand study (Blakely *et al.*, 2020) predicted a 16% increase in fruit and 30% increase in vegetable consumption with 20% subsidies. In an Australian study (Cobiac *et al.*, 2017), subsidies increased fruit and vegetable intake but also overall sodium and energy intake. We saw a similar cross price effects in our study, with increases in meat prices having the unwanted consequence of increasing alcohol purchases, particularly among low-income households. One disadvantage of fiscal disincentives is the potential to increase inequalities as households in lower incomes will be hit harder than those with higher incomes. This type of policy could therefore be perceived as less desirable from a social justice point of view. In 2019, the lowest 20% of households by equivalised income had lower mean purchases of meat, dairy and fruit and vegetables compared to the whole sample. They also had a higher proportion of spending on food and non-alcoholic drinks (14.7%) compared to the average household (10.6%) (UK Government, 2019). Both fiscal scenarios predicted larger decreases in animal products in low-income households. However, the fruit and vegetable subsidy had similar positive effects on intakes regardless of income. This is in contrast with previous findings in a French study (Darmon *et al.*, 2016) where a simulated subsidy on fruit and vegetable resulted in medium income women decreasing their energy density by a larger extent than low-income women. It is also important to highlight that fiscal disincentives are a controversial policy for reducing meat consumption, regardless of household income.

Our findings indicate that the recommendation of the National Food Strategy to invest in innovation to create a better food system could result in reduced GHG emissions and water use from diets and also reduced ill health from over-consumption of red and processed meat. Both reformulation of processed foods and precision fermentation are suggested as ways to use innovation funds to shift consumer intake towards healthier and more sustainable diets. The choice experiment studies (Van Loo *et al.*, 2020, Slade *et al.*, 2018) we used to model consumer behaviour show a marked preference of consumers for plant-based alternatives compared to laboratory produced meat. Unlike plant-based alternatives, cultured meat is not yet available in most countries, including the UK, which makes forecasts about its uptake and acceptability less reliable. However, the US Food and Drug Administration

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has recently cleared a lab-grown meat product for human consumption (Reuters news, 2022). Recent analyses of the National Diet and Nutrition Survey found that the proportion of people consuming plant-based alternative foods and drinks had nearly doubled from 6.7% in 2008 to 13.1% in 2019 (Alae-Carew *et al.*, 2021). Because of the increasing popularity and availability on the British market of plant based meat and dairy, it is necessary to ensure that both currently available and future products are healthy as well as sustainable. A recent UK paper (Alessandrini *et al.*, 2021) found that compared to equivalent meat products, plant-based meat products had significantly lower energy density and saturated fat and higher fibre, but that three quarters of the products did not meet the UK salt targets. More research into the nutritional and health benefits of the expanding market of plant-based meat and dairy alternatives is necessary.

Increased fruit and vegetable consumption can increase the UK's environmental footprint abroad, given that a substantial proportion of these fruits and vegetables are likely to be produced abroad and currently more than 80% of fresh fruit and 50% of vegetables are imported. In particular, given the water intensity of fruit and vegetable products, this can be of concern in countries which suffer from water scarcity. Moreover, previous research has shown that an important proportion of the fruit and vegetable imports in the UK come from climate vulnerable countries (Scheelbeek *et al.*, 2020). On the other hand, animal feed imports in Europe and UK have been found to be directly linked to deforestation in producing countries (Pendrill et al, 2019). Therefore, it is possible that reduced meat consumption and production can have positive spill-overs in other countries through reduced demand for feed crop production overseas. A lot of processed food uses palm oil, which is entirely produced overseas, typically with large environmental impacts (Busch & Austin. 2022). If processed mat alternatives contain palm oil this could affect the environmental footprint of the UK abroad. However, the net effect is likely to be positive given the differential in land use per calorie between plant-based foods and meat conversion.

Our study had several strengths. The analyses contribute new evidence on the potential of food policies to help reach the CCC meat and dairy reduction targets. We used 19 years of nationally representative household data, which make our analyses generalisable to the UK population. We also attempted to quantify the uncertainties in all our scenario estimates using Monte Carlo simulation. Another strength of our study is the calculation of GHG emissions and water use considering the proportion of imports of each food product (i.e. consumption-based rather than production-based footprints). For some foods,

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such as beef, whose footprint changes considerably depending on the country of production, this is very important.

The study also had several limitations. We decided to use the CCC target as it is a feasible and realistic target and the one endorsed by the Government to achieve net zero; however it should be emphasised that to achieve net zero emissions in the UK, actions to reduce emissions will also be needed in other sectors. All analyses are hypothetical scenarios which are based on assumptions and should be interpreted with care. The LCF survey is household purchasing data which likely overestimates intakes as food waste is not accounted for. Including food waste might also give a more realistic picture of the environmental impact of food systems. The data are based on self-reported estimates of food purchase and thus subject to recall bias and possible under-reporting of undesirable food items, such as confectionery and alcohol. However, receipts of purchases were used in the Family Food survey making it more reliable than just using questionnaires.

We based our dietary analyses on various evidence, including past trends, prior estimations of price elasticates and demand estimates from choice experiments. All these sources have several limitations. Although we performed several tests before selecting what we believed to be the most appropriate BAU scenarios there is no certainty that future trends will continue in the same direction as past ones. This type of analysis cannot account for unpredictable events and ignores other potential drivers of intake such as future trade deals, environmental shifts and policies that affect availability and price. The recent move of the UK out of the European Union will most likely affect these factors. The fiscal model also contains some uncertainty as different methods of calculating price elasticises will produce different results (see Figure 1S) and it is possible that consumer preferences and incomes change over time meaning that their price responsiveness can change as well. Elasticities used in this study were estimated from 2009 data which was the only source available that matched the food groups used in this study. We used discrete choice experiment studies to predict future consumer behaviour, but these are based on hypothetical choices in researcher controlled settings meaning the stated preferences may not translate into real purchases and other influences apart from price and taste might be or might become important. The studies we used were based in the US and Canada and might not represent UK consumers. However, our predictions of plant-based meat and dairy substitute intakes are likely to be conservative given the sharp increase in the most recent years (Alae-Carew *et al.*, 2021). The calculation of the amount and type of foods that will substitute farmed meat and dairy in the production of laboratory produced animal products is mostly based on studies reporting current production, which is not intended for mass consumer consumption. Expensive medical grade feedstock is currently used, and the most appropriate and cost-effective feedstock will most likely change in the future. Based on current studies (Post *et al.*, 2012; Lynch *et al.*, 2019) we assumed soy, wheat, maize and cyanobacteria as the most likely feedstock for animal cells. As some of these are already currently fed to farmed animals, this prediction is likely to be partly confirmed. Finally, the GHG factors applied in our study are based on current carbon production intensity and do not take into account potential future improvements in energy efficiency and use of renewables, which would result in lower CO_2 estimates.

In conclusion, our study supports the implementation of various policies to help the UK transition to healthier and more sustainable dietary patterns. Our modelling scenarios revealed that encouraging people to switch to meat and dairy alternatives would enable the UK to meet its net zero target but the nutritional properties of these alternatives may not always be beneficial. This is supported by the latest National Food Strategy, which recommended technological and food system innovation as the preferred strategy to shift consumption. Fiscal measures would lead to higher fruit and vegetable intakes but only if a meat tax was combined with a subsidy. If no action is taken and current trends continue into the future, the UK food sector will not be able to meet its zero net emission targets, and so policies such as the ones modelled here should be given urgent consideration.

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