

Reduced meat and dairy consumption improves health, environmental and most nutritional outcomes without increasing diet costs among Scottish adults

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Shifting diets away from high levels of meat and dairy is increasingly considered an important part of climate mitigation, yet the best pathways for achieving these reductions without compromising nutrition, health or affordability remain unclear. Here, in a representative sample of Scottish adults, we evaluate 33 pathways to meeting the UK Climate Change Committee's recommendations to reduce meat and dairy consumption by 20% by 2030, increasing to a 35% reduction in meat by 2050. The pathways incorporate existing dietary guidance, and modelled outcomes include intakes of 54 nutrients, obesity, type 2 diabetes, cardiovascular disease, all-cause mortality, diet costs, greenhouse gas emissions, freshwater use, land use and eutrophication. Nearly all pathways were estimated to benefit most nutritional, health and environmental outcomes without increasing diet costs. Benefits were greater when reductions targeted high consumers of red meat and when meat and dairy were replaced gram for gram with foods such as vegetables, beans, eggs and plant-based dairy alternatives.

Reducing the consumption of animal source foods has been recommended in high-consuming countries to help meet environmental targets¹. In the UK, the Climate Change Committee (CCC) has recommended a reduction in all meat and dairy consumption by 20% by 2030, increasing to a reduction of 35% in meat consumption by 2050². However, dietary guidance in the UK, known as the Eatwell Guide, focuses specifically on eating less red and red processed meat³, given evidence of an association between regular consumption of high levels of red

and processed meat with increased risk of developing several chronic diseases^{4,5}. The Scottish Dietary Goals set a recommended maximum intake of red and red processed meat at 70 g per day⁶. There is a gap in understanding the most effective pathway to meeting the UK CCC dietary recommendations, taking into account existing dietary guidance, impacts on nutrient intake, chronic disease risk, greenhouse gas (GHG) emissions as well as other environmental outcomes such as water and land use, and eutrophication. The transition to net zero must be

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Table 1 | Summary of meat and dairy reduction pathways and outcomes assessed

	Pathway name	Reduction in meat	Reduction in dairy	Replacement of meat	Replacement of dairy	Outcomes assessed			
						Nutrient intake	Environment ^a	Cost of diets	Health ^b
1	CCC 2030, no replacement	20% reduction in all meat	20% reduction in all dairy	None	None	✓	✓	✓	✓
2	CCC 2030, beans and PBDA			Beans/pulses	PBDA ^c	✓	✓	✓	
3	CCC 2030, vegetables and PBDA			Vegetables		✓	✓	✓	
4	CCC 2030, eggs and PBDA			Eggs		✓	✓	✓	
5	CCC 2030, fish and PBDA			Non-smoked oily fish		✓	✓	✓	
6	CCC 2030, PBMA and PBDA			PBMA		✓	✓	✓	
7	CCC 2050, no replacement	35% reduction in all meat	20% reduction in all dairy	None	None	✓	✓	✓	✓
8	CCC 2050, beans and PBDA			Beans/pulses	PBDA ^c	✓	✓	✓	
9	CCC 2050, vegetables and PBDA			Vegetables		✓	✓	✓	
10	CCC 2050, eggs and PBDA			Eggs		✓	✓	✓	
11	CCC 2050, fish and PBDA			Non-smoked oily fish		✓	✓	✓	
12	CCC 2050, PBMA and PBDA			PBMA		✓	✓	✓	
13	SDG, no replacement	Red meat reduced to max 70 g per day ^d	20% reduction in all dairy	None	None	✓	✓	✓	✓
14	SDG, beans and PBDA			Beans and pulses	PBDA ^c	✓	✓	✓	
15	SDG, vegetables and PBDA			Vegetables		✓	✓	✓	
16	SDG, eggs and PBDA			Eggs		✓	✓	✓	
17	SDG, fish and PBDA			Non-smoked oily fish		✓	✓	✓	
18	SDG, PBMA and PBDA			PBMA		✓	✓	✓	
19	SDG, poultry and PBDA			Poultry		✓	✓	✓	
20	Red meat 60 g per day max, no replacement	Red meat reduced to max 60 g per day ^e	20% reduction in all dairy	None	None	✓	✓	✓	✓
21	Red meat 60 g per day max, beans and PBDA			Beans and pulses	PBDA ^c	✓	✓	✓	
22	Red meat 60 g per day max, vegetables and PBDA			Vegetables		✓	✓	✓	
23	Red meat 60 g per day max, eggs and PBDA			Eggs		✓	✓	✓	
24	Red meat 60 g per day max, fish and PBDA			Non-smoked oily fish		✓	✓	✓	
25	Red meat 60 g per day max, PBMA and PBDA			PBMA		✓	✓	✓	
26	Red meat 60 g per day max, poultry and PBDA			Poultry		✓	✓	✓	
27	Red meat 31 g per day max, no replacement	Red meat reduced to max 31 g per day ^f	20% reduction in all dairy	None	None	✓	✓	✓	✓
28	Red meat 31 g per day max, beans and PBDA			Beans and pulses	PBDA ^c	✓	✓	✓	
29	Red meat 31 g per day max, vegetables and PBDA			Vegetables		✓	✓	✓	
30	Red meat 31 g per day max, eggs and PBDA			Eggs		✓	✓	✓	
31	Red meat 31 g per day max, fish and PBDA			Non-smoked oily fish		✓	✓	✓	
32	Red meat 31 g per day max, PBMA and PBDA			PBMA		✓	✓	✓	
33	Red meat 31 g per day max, poultry and PBDA			Poultry		✓	✓	✓	
34	20% dairy reduction, no replacement	None	20% reduction in all dairy	None	None	✓	✓	✓	✓
35	20% dairy reduction, PBDA	None	20% reduction in all dairy	None	PBDA ^c	✓	✓	✓	

All meat includes beef, lamb, pork, processed red meat, other red meat, burgers, sausages, offal, poultry, processed poultry and game birds. Red meat includes beef, lamb, pork, processed red meat, other red meat, burgers, sausages and offal. Replacements of meat and dairy were gram for gram. PBDA, plant-based dairy alternatives; PBMA, plant-based meat alternatives; SDG, Scottish Dietary Goal. ^aEnvironmental outcomes included GHG emissions, water and land use, and eutrophication. ^bHealth outcomes included prevalence of obesity, the incidence of type 2 diabetes, cardiovascular disease and all-cause mortality. ^cPlant-based dairy alternatives included plant-based milks, yoghurts and solid fats but not cheese given limited availability in the Scottish food retail environment. ^dScottish Dietary Goal for red meat. ^e60 g per day is the amount of reduction in red meat that would achieve an overall reduction in all meat of 20%, the CCC target for 2030. ^f31 g per day is the amount of reduction in red meat that would achieve an overall reduction in all meat of 35%, the CCC target for 2050.

affordable to avoid perpetuating or exacerbating health inequalities, and so pathways should also account for the cost of dietary transitions, particularly for low-income households.

In Scotland, where the CCC dietary recommendations have been ‘partially accepted’⁷, no study has explored the impact of meat and dairy reductions on nutrient intake, chronic disease risk, the environment and cost of diets overall or in specific population subgroups—especially among those living in the most deprived areas. UK-wide studies have generally estimated the effect in the whole population, modelling the impact of a reduction in meat replaced with fruit, vegetables, legumes and/or cereals on nutrient intake, mortality and/or GHG emissions^{8–12}. Comparatively few studies have evaluated concurrent reductions in dairy, the impact on the cost of diets, variations in impacts by population subgroup or replacement with plant-based meat and dairy alternatives^{9,13,14}.

In the present study, we employed a microsimulation, which enables estimation by population subgroup, to quantify how different pathways to achieving the CCC recommendations affected dietary intake of 54 nutrients; the prevalence of obesity and the incidence of type 2 diabetes, cardiovascular disease and all-cause mortality; cost of diets; and GHG emissions, freshwater use (herein water use), land use and eutrophication. Dietary intake, including nutrient intake, and health data were from the latest round of the Scottish Health Survey (SHeS 2021), which is designed to be representative and included adults 16 years and older. Data on environmental impact and diet cost were taken from foodDB, a product-specific dataset containing the estimated environmental impact and price of approximately 70,000 items available in UK supermarkets^{15,16}, which we matched to dietary intake data reported in SHeS. We also provide estimates for the population-level yearly dietary emissions adjusted for underreported caloric intake in SHeS 2021.

We evaluated 33 meat and dairy reduction pathways (Table 1). Pathways focused on reductions in all meat (beef, lamb, pork and poultry; herein ‘meat’) as specified in the CCC dietary recommendations, or reductions in red and red processed meat (beef, lamb and pork; herein ‘red meat’) among high consumers as specified in the Scottish Dietary Goals, together with reductions in all dairy. ‘High consumers’ were those consuming above the maximum threshold for red meat—either 70 g per day, 60 g per day or 31 g per day, depending on the pathway. To help interpret the combined effects of meat and dairy reductions, we ran two additional pathways: a 20% reduction in dairy with no reduction in meat consumption, both with and without a plant-based dairy alternative substitution. We did not consider maximum intake thresholds for dairy as there is no such guideline in the Scottish Dietary Goals. For each meat and dairy reduction pathway, we considered gram-for-gram replacement of meat with beans and pulses, vegetables, eggs, non-smoked oily fish, plant-based meat alternatives or (for red meat reduction pathways only) poultry; and a gram-for-gram replacement of dairy with plant-based milks, yoghurts and solid fats and no replacement for cheese. We chose gram-for-gram replacements because a calorie-for-calorie replacement would be more difficult for individuals to adopt given limited consumer knowledge and understanding of calories¹⁷. While we provide the results for health outcomes assuming an isocaloric substitution in Supplementary Information, gram-for-gram replacement of meat with other foods may result in a modest decrease in caloric intake and associated greater health benefits compared with the isocaloric results. We did not consider plant-based cheeses given limited availability in the Scottish food retail environment¹⁸.

Given the large number of pathways (35 total) and outcomes (63 total) evaluated, overall and by population subgroup (sex, 10-year age groups (16–24 years, 25–34 years, 35–44 years and so on) and Scottish Index of Multiple Deprivation (SIMD) quintiles), we chose to highlight specific pathways and outcomes in the text. Results for all outcomes for all reduction pathways by population subgroups are provided in

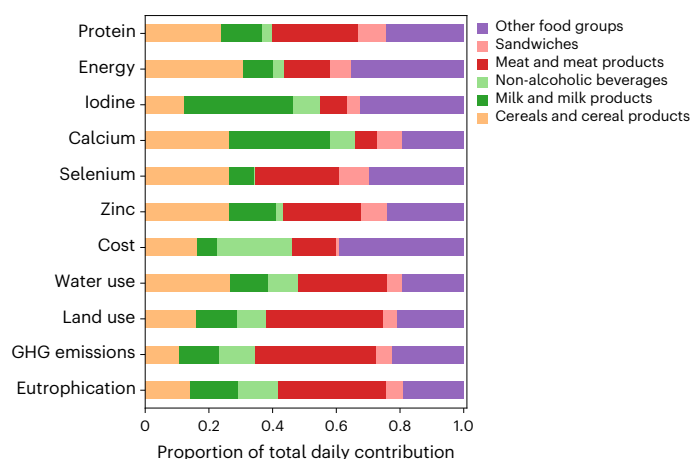


Fig. 1 | Food category relative contributions at baseline. Relative contribution of each food category to intake of select nutrients, food costs and environmental indicators in a representative sample of adults 16+ years living in Scotland (2021) ($n = 3,447$).

Supplementary Data. In the text, we highlight pathway 27—a reduction in red meat to a maximum of 31 g per day together with a 20% reduction in all dairy, and no replacement—as the ‘most effective pathway’ because this pathway resulted in the greatest benefits for health and the environment together with dietary cost savings. Impacts on intakes of calcium, iodine, zinc and selenium are highlighted because meat and dairy were previously identified as important sources of these nutrients in Scottish diets¹⁹. We further highlight impacts on cardiovascular disease by population subgroup because cardiovascular disease is the leading cause of death in Scotland²⁰.

Results

Baseline diets

In 2021, total GHG emissions associated with food consumed by adults living in Scotland were estimated to be 10.4 Mt CO₂ equivalents (CO₂e) (95% uncertainty interval (UI), 10.3 to 10.6 MtCO₂e) after adjusting for underreported daily caloric intake (Supplementary Information p. 17). Mean unadjusted (95% UI) per capita daily GHG emissions were 4.34 kgCO₂e (4.24 to 4.44 kgCO₂e), and the cost of diets was £8.88 (£8.65 to £9.10). Meat and meat products were the largest contributor to each environmental outcome, accounted for 14% of the cost of diets and were responsible for approximately a quarter of protein, zinc and selenium intake. Milk and milk products accounted for 6% of diet cost, 10–15% of each environmental outcome, and a third of iodine and calcium intake (Fig. 1 and Supplementary Data).

Health and nutritional outcomes

In the most effective pathway (pathway 27), the average drop in daily protein intake was 9.1 g, or 13.5%, compared with an average per capita daily intake at baseline of 67.2 g (Table 2 and Fig. 2a). The decrease in calcium intake in the pathways with no replacement was largely driven by the decrease in dairy, with 92% of the decrease in calcium intake in the most effective pathway resulting from the dairy reduction, corresponding to an ~10% decrease in per capita calcium intake. The age group 16–24 years started with the lowest baseline per capita intake of all other age groups at an average of 749 mg per day, which decreased to 665 mg per day in the most effective pathway. However, this decrease in calcium intake was compensated in all age groups when red and red processed meat was replaced with plant-based meat alternatives (Fig. 2b and Supplementary Data). The decrease in iodine intake was also driven by the decrease in dairy, with 87% of the decrease in iodine intake in the most effective pathway arising from dairy reduction corresponding to an ~11% decrease in per capita iodine intake. Given the lack of iodine in

Table 2 | Mean (95% UI) impact of reducing meat and dairy from baseline (2021) levels with no replacement on nutrient intake, environmental outcomes, cost of diets and chronic disease in a representative sample of adults 16+ years living in Scotland

Pathway ^a	CCC 2030	CCC 2050	Scottish Dietary Goal (red meat 70 g per day max)	Red meat 60 g per day max	Red meat 31 g per day max	Dairy reduction, 20%
Change in per capita nutrient intake						
Protein, g per day	-6.77 (-8.69 to -4.85)	-9.85 (-11.73 to -7.97)	-5.61 (-7.53 to -3.69)	-6.29 (-8.21 to -4.37)	-9.09 (-11.01 to -7.18)	-2.67 (-4.65 to -0.69)
Zinc, mg per day	-0.71 (-0.93 to -0.49)	-1.00 (-1.22 to -0.78)	-0.74 (-0.96 to -0.52)	-0.83 (-1.04 to -0.62)	-1.23 (-1.45 to -1.01)	-0.33 (-0.55 to -0.11)
Calcium, mg per day	-85.17 (-111.32 to -59.02)	-87.36 (-113.53 to -61.19)	-85.36 (-111.45 to -59.27)	-86.08 (-112.19 to -59.97)	-89.09 (-115.24 to -62.94)	-82.24 (-108.37 to -56.11)
Iodine, µg per day	-15.96 (-22.35 to -9.57)	-16.87 (-23.28 to -10.46)	-15.72 (-22.11 to -9.33)	-15.96 (-22.35 to -9.57)	-16.96 (-23.37 to -10.55)	-14.74 (-21.13 to -8.35)
Selenium, µg per day	-2.78 (-4.52 to -1.04)	-4.30 (-6.02 to -2.58)	-2.12 (-3.86 to -0.38)	-2.43 (-4.17 to -0.69)	-3.71 (-5.45 to -1.97)	-0.74 (-2.5 to 1.02)
Change in per capita consumption impacts						
GHG emissions, kgCO ₂ e per day	-0.47 (-0.59 to -0.35)	-0.71 (-0.83 to -0.59)	-0.49 (-0.61 to -0.37)	-0.57 (-0.69 to -0.45)	-0.91 (-1.03 to -0.79)	-0.15 (-0.27 to -0.03)
Land use, m ² per day	-0.61 (-0.79 to -0.43)	-0.94 (-1.12 to -0.76)	-0.66 (-0.84 to -0.48)	-0.77 (-0.95 to -0.59)	-1.25 (-1.41 to -1.09)	-0.18 (-0.38 to 0.02)
Eutrophication, gPO ₄ e per day	-1.85 (-2.3 to -1.4)	-2.68 (-3.11 to -2.25)	-1.94 (-2.37 to -1.51)	-2.23 (-2.66 to -1.8)	-3.47 (-3.9 to -3.04)	-0.72 (-1.19 to -0.25)
Water use, litres per day	-39.66 (-57.54 to -21.78)	-58.22 (-76.0 to -40.44)	-42.18 (-59.94 to -24.42)	-48.52 (-66.26 to -30.78)	-75.24 (-93.0 to -57.48)	-14.78 (-32.87 to 3.31)
Change in per capita price						
£ per day	-0.29 (-0.60 to 0.03)	-0.41 (-0.72 to -0.10)	-0.25 (-0.56 to 0.07)	-0.28 (-0.59 to 0.04)	-0.41 (-0.72 to -0.09)	-0.12 (-0.43 to 0.20)
Health outcomes over 10 years						
Prevented type 2 diabetes cases	36,491 (30,906 to 42,098)	49,179 (41,122 to 56,906)	38,970 (32,571 to 45,172)	43,162 (35,671 to 50,359)	59,248 (46,609 to 70,675)	17,740 (14,680 to 20,089)
Prevented cardiovascular disease cases	9,675 (7,080 to 12,213)	14,060 (9,727 to 18,179)	10,177 (7,408 to 13,040)	11,695 (8,029 to 15,247)	18,595 (11,264 to 25,721)	4,567 (4,190 to 4,949)
Per capita change in BMI, kg m ⁻²	-1.53 (-1.54 to -1.52)	-1.96 (-1.97 to -1.95)	-1.47 (-1.48 to -1.46)	-1.59 (-1.6 to -1.58)	-2.09 (-2.1 to -2.07)	-0.96 (-0.96 to -0.95)
Prevented all-cause mortality	1,236 (932 to 1,496)	1,741 (1,247 to 2,170)	1,225 (904 to 1,521)	1,456 (1,042 to 1,799)	2,240 (1,729 to 2,726)	552 (475 to 610)

^aPathways: 'CCC 2030', a 20% reduction in all meat and dairy; 'CCC 2050', a 35% reduction in all meat and 20% reduction in all dairy; 'Scottish Dietary Goal (red meat 70 g per day max)', reducing red meat to a maximum intake of 70 g per day and 20% reduction in all dairy; 'Red meat 60 g per day max', reducing red meat to a maximum intake of 60 g per day and 20% reduction in all dairy; and 'Red meat 31 g per day max', reducing red meat to a maximum intake of 31 g per day and 20% reduction in all dairy.

the oat milk represented in the UK nutrient databank, which made up ~50% of the plant-based replacement for dairy milk (Supplementary Information p. 8), replacement of dairy with plant-based milks, yogurts and solid fats did not substantially increase iodine intake (Fig. 2c).

In the most effective pathway, over 10 years, there were 59,248 (95% UI, 46,609 to 70,675) prevented type 2 diabetes cases (~25.5% of annual cases), 18,595 (11,264 to 25,721) prevented cardiovascular disease cases (~5.8% of annual cases), a population average change in body mass index (BMI) of -2.09 kg m⁻² (-2.10 to -2.07 kg m⁻²) and 2,240 (1,729 to 2,726) prevented all-cause mortalities (~3.9% of annual deaths) (Table 2). Compared with an equivalent pathway assuming isocaloric substitution, 66% of the prevented type 2 diabetes cases were a result of weight loss (Supplementary Table 12).

Environmental outcomes

All pathways resulted in a significant net reduction in GHG emissions, with pathways involving the reduction of red meat in high consumers having slightly greater reductions in dietary GHG emissions relative to the equivalent CCC pathway (Table 2). For example, the CCC

2030 pathway with no replacement decreased GHG emissions by 0.47 kgCO₂e per capita per day (95% UI, -0.59 to -0.35 kgCO₂e per capita per day) whereas achieving the same overall reduction in all meat by reducing red meat in high consumers (red meat 60 g per day max pathway) resulted in a decrease of 0.57 kgCO₂e per capita (including non-consumers) per day (-0.69 to -0.45 kgCO₂e per capita per day). A similar pattern was observed for other environmental outcomes. All meat and dairy replacement pathways resulted in significant net reductions in all environmental outcomes (Fig. 3a-d).

Diet costs

The average cost decreased by £0.41 per day (95% UI, -£0.72 to -£0.09) in the most effective pathway (Fig. 4 and Table 2) and by £0.41 per day (95% UI, -£0.72 to -£0.10) in the equivalent CCC pathway (pathway 7). Replacement with vegetables or pulses and legumes retained the greatest average cost savings in the most effective pathway, with both resulting in an average cost saving of £0.15 per day (95% UI, -£0.16 to £0.46). Replacement with oily fish in this pathway and the equivalent CCC pathway (pathway 11) resulted in the only statistically significant

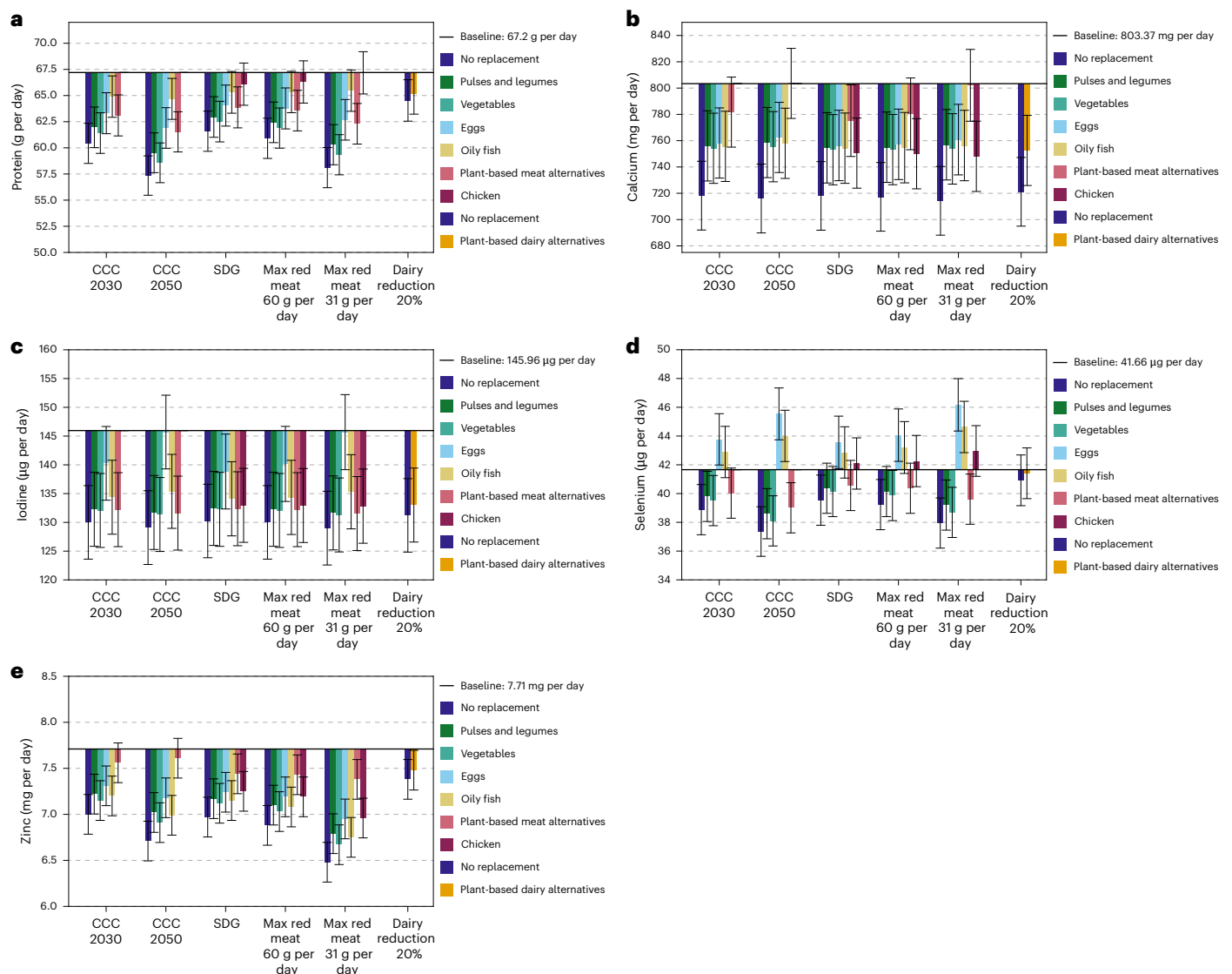


Fig. 2 | Impact on nutrient intake in each pathway. a–e. Impact on per capita intake of protein (g per day) (**a**), calcium (mg per day) (**b**), iodine (μ g per day) (**c**), selenium (μ g per day) (**d**) and zinc (mg per day) (**e**) in each meat and dairy reduction pathway in a representative sample of adults 16+ years living in

Scotland ($n = 3,447$). Each bar represents the difference between the mean per capita intake at baseline and each pathway. Error bars represent 95% UIs, calculated as 1.96 multiplied by the standard error of the difference in intake at baseline and each pathway.

increase in cost, with an increase of £0.39 per day (95% UI, £0.08 to £0.71) and £0.38 per day (95% UI, £0.07 to £0.70) respectively. There was no significant difference in cost savings between the most and least deprived quintiles in the most effective pathway, at £0.40 per day (95% UI, –£0.59 to £1.39) and £0.38 per day (95% UI, –£0.13 to £0.90) respectively. Demographic differences for other outcomes in the most effective pathway are provided in Table 3 and for all pathways in Supplementary Data.

Discussion

We found that the CCC recommendations to reduce overall meat consumption by 20% by 2030, rising to 35% by 2050², can be achieved in Scotland by reducing red meat consumption in high consumers to a maximum of 60 g per day and 31 g per day, respectively. Results of our nationally representative simulation suggest that such an emphasis on red meat consumption in high consumers of red meat would prevent more chronic disease cases, produce slightly greater reductions in environmental harms—not just GHG emissions but also land and water use, as well as eutrophication—and have comparable cost savings. Currently,

meat and meat products in Scotland account for a small proportion of the cost of diets and nutrient intake relative to their contribution to environmental harms. Dairy, meanwhile, accounts for a smaller portion of the cost of diets and environmental harms than meat and is a substantial source of key nutrients such as calcium and iodine. Thus, reducing dairy consumption would have a smaller impact on environmental harms and food expenditure than reducing red meat consumption, while carrying a greater risk of introducing or exacerbating nutrient deficiencies in certain population groups based on current Scottish dietary patterns. Gram-for-gram replacements of meat and dairy with nutrient rich substitutes ranging from vegetables to beans to eggs can attenuate effects on nutrient intake, improve adherence to dietary guidance for fruit and vegetables, and provide environment benefits with little impact on diet costs.

We found that total GHG emissions associated with food consumed by adults living in Scotland—estimated in our analysis to be 10.4 MtCO₂e—exceed those of the agricultural sector in Scotland (7.7 MtCO₂e)²¹, further supporting the need for a change in food consumption patterns alongside changes in production practices. This

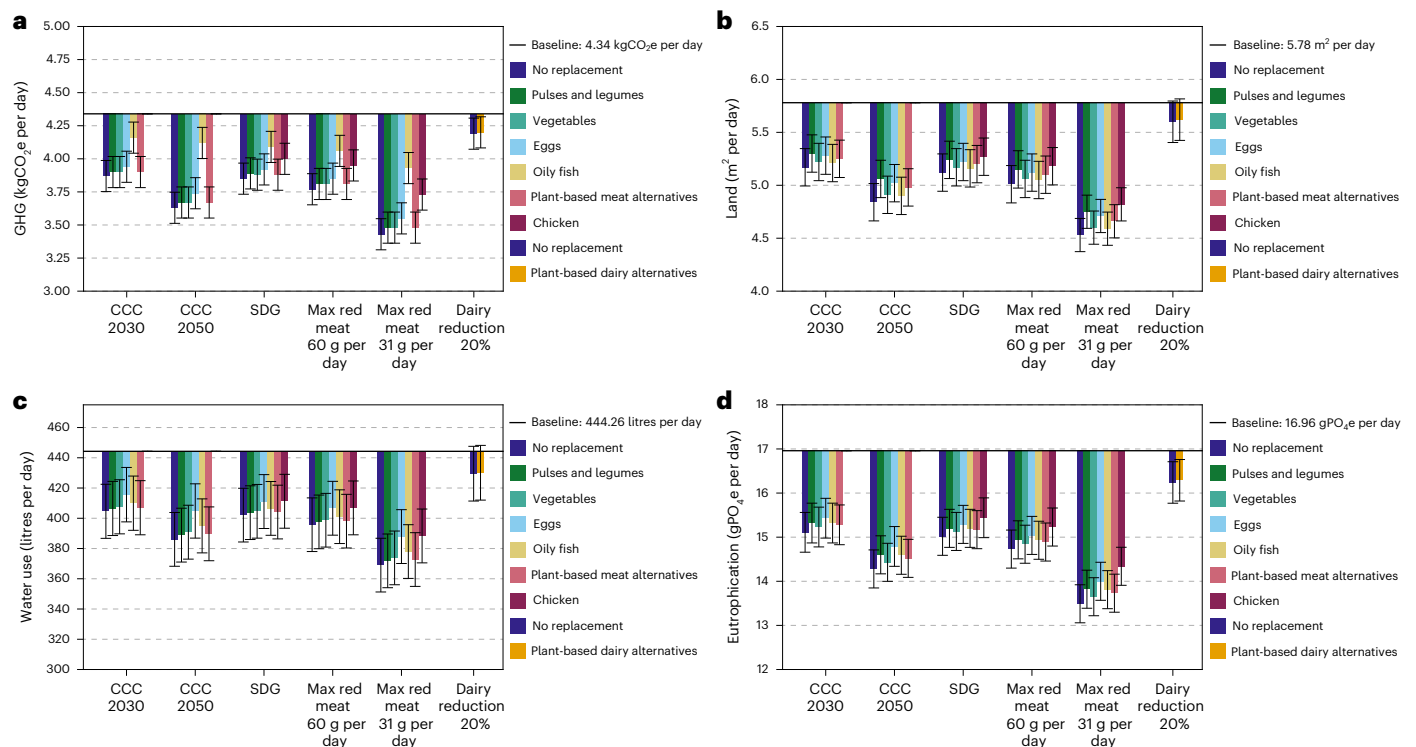


Fig. 3 | Impact on environmental impacts in each pathway. a–d, Impact on per capita GHG emissions (kgCO₂e per day) (a), land use (m² per day) (b), water use (litres per day) (c) and eutrophication (gPO₄e per day) (d) in each meat and dairy reduction pathway in a representative sample of adults 16+ years living

in Scotland ($n = 3,447$). Each bar represents the difference between the mean per capita impacts at baseline and each pathway. Error bars represent 95% UIs, calculated as 1.96 multiplied by the standard error of the difference in impact at baseline and each pathway. GHG, GHG emissions.

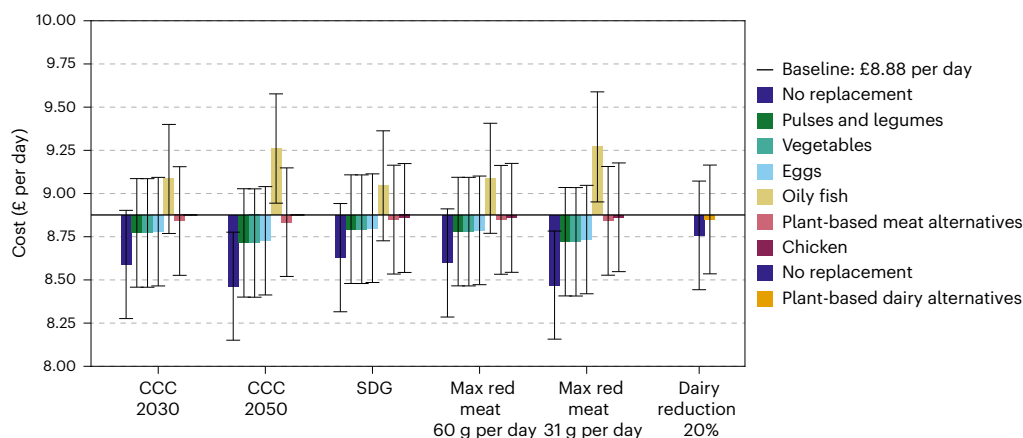


Fig. 4 | Impact on diet cost in each pathway. Impact on the per capita cost of diets in each meat and dairy reduction pathway in a representative sample of adults 16+ years living in Scotland ($n = 3,447$). Each bar represents the difference

between the mean per capita diet costs at baseline and each pathway. Error bars represent 95% UIs, calculated as 1.96 multiplied by the standard error of the difference in cost at baseline and each pathway.

discrepancy arises in part from Scotland's reliance on food imports, particularly pork, chicken, white fish and out-of-season fruits and vegetables²². The most comprehensive analysis of GHG emissions from food consumed in the UK, including imported food, estimated emissions of 154.8 MtCO₂e in 2020²³. Assuming emissions are proportional to population, this would amount to 12.7 MtCO₂e per year in Scotland. The difference is probably due to the inclusion of packaging, transport, waste disposal and energy use by food retailers, hospitality, food service and households²³, which were excluded from the life cycle assessment database in our analysis^{15,16}. Together, these stages of the food supply chain accounted for 24% of total emissions²³; not

accounting for these would amount to about 9.6 MtCO₂e per year, which is similar to our estimate.

The cost savings from the most effective pathway were £0.40 per day for those living in the most deprived areas of Scotland and £0.38 per day for those in the least deprived when meat and dairy were not replaced. When replaced with vegetables or legumes, the average cost savings were £0.15 per day in both pathways. These results are comparable to a previous diet optimization study that found an average saving of £0.21 per day¹⁴. By contrast, that study found greater cost savings in higher-income households (£0.47 per day) as compared with lower-income households (£0.23 per day)¹⁴, while we did not find

Table 3 | Mean per capita impacts (95% UI^a) on nutrient intake (zinc, calcium, iodine and selenium), the environment (GHG emissions), cost of diets and chronic disease incidence (cardiovascular disease) in the most effective pathway, reducing red meat intake to a maximum of 31g per day together with a 20% reduction in all dairy with no replacement across population subgroups in a representative sample of adults 16+ years living in Scotland

	Zinc, mg per day	Calcium, mg per day	Iodine, µg per day	Selenium, µg per day	Dietary GHG emissions, kgCO ₂ e per day	Cost of diets, £ per day	Cardiovascular disease, prevented cases over 10 years
Men	-1.48 (-1.81 to -1.15)	-94.18 (-141.69 to -46.67)	-18.00 (-28.84 to -7.16)	-4.59 (-7.12 to -2.06)	-1.1 (-1.28 to -0.92)	-0.48 (-0.99 to 0.04)	12,178 (7,300 to 16,712)
Women	-1.0 (-1.24 to -0.76)	-84.34 (-109.58 to -59.1)	-15.98 (-21.66 to -10.30)	-2.89 (-4.56 to -1.22)	-0.73 (-0.87 to -0.59)	-0.34 (-0.64 to -0.04)	6,417 (3,963 to 8,998)
16–24 years	-1.17 (-2.19 to -0.15)	-84.33 (-198.11 to 29.45)	-15.56 (-32.98 to 1.86)	-3.83 (-9.71 to 2.05)	-0.96 (-1.43 to -0.49)	-0.42 (-1.57 to 0.73)	62 (35 to 87)
25–34 years	-1.1 (-1.57 to -0.63)	-78.09 (-136.13 to -20.05)	-14.14 (-26.25 to -2.03)	-3.52 (-7.2 to 0.16)	-0.8 (-1.11 to -0.49)	-0.36 (-1.08 to 0.36)	258 (147 to 372)
35–44 years	-1.37 (-1.9 to -0.84)	-95.82 (-158.5 to -33.14)	-17.55 (-32.98 to -2.12)	-4.08 (-7.57 to -0.59)	-0.98 (-1.27 to -0.69)	-0.46 (-1.13 to 0.22)	1,044 (584 to 1,500)
45–54 years	-1.22 (-1.73 to -0.71)	-88.05 (-147.18 to -28.92)	-16.39 (-28.48 to -4.3)	-3.5 (-6.66 to -0.34)	-0.91 (-1.2 to -0.62)	-0.38 (-1.10 to 0.34)	2,457 (1,394 to 3,451)
55–64 years	-1.29 (-1.66 to -0.92)	-91.53 (-139.57 to -43.49)	-17.76 (-28.29 to -7.23)	-3.85 (-6.61 to -1.09)	-0.93 (-1.17 to -0.69)	-0.41 (-0.96 to 0.14)	4,496 (2,600 to 6,380)
65–74 years	-1.3 (-1.69 to -0.91)	-94.28 (-144.89 to -43.67)	-19.11 (-33.22 to -5.0)	-3.71 (-6.49 to -0.93)	-0.94 (-1.19 to -0.69)	-0.42 (-0.91 to 0.06)	5,631 (3,647 to 7,403)
75+ years	-1.16 (-1.63 to -0.69)	-93.46 (-165.24 to -21.68)	-19.11 (-38.61 to 0.39)	-3.44 (-7.36 to 0.48)	-0.85 (-1.2 to -0.5)	-0.39 (-1.13 to 0.35)	4,644 (2,853 to 6,487)
SIMD 1 (most deprived)	-1.28 (-1.85 to -0.71)	-80.43 (-140.6 to -20.26)	-15.41 (-30.44 to -0.38)	-4.2 (-9.55 to 1.15)	-1.03 (-1.32 to -0.74)	-0.40 (-1.39 to 0.59)	2,620 (1,469 to 3,772)
SIMD 2	-1.29 (-1.64 to -0.94)	-87.45 (-127.26 to -47.64)	-17.43 (-27.31 to -7.55)	-3.66 (-6.17 to -1.15)	-0.93 (-1.18 to -0.68)	-0.41 (-1.04 to 0.23)	4,272 (2,495 to 5,966)
SIMD 3	-1.23 (-1.64 to -0.82)	-90.99 (-142.38 to -39.6)	-17.13 (-28.6 to -5.66)	-3.84 (-6.88 to -0.8)	-0.89 (-1.2 to -0.58)	-0.42 (-0.93 to 0.09)	4,895 (3,106 to 6,664)
SIMD 4	-1.22 (-1.67 to -0.77)	-89.09 (-137.8 to -40.38)	-16.83 (-27.16 to -6.5)	-3.56 (-5.87 to -1.25)	-0.92 (-1.17 to -0.67)	-0.42 (-0.98 to 0.14)	2,955 (1,639 to 4,283)
SIMD 5 (least deprived)	-1.15 (-1.56 to -0.74)	-96.52 (-144.01 to -49.03)	-17.78 (-31.17 to -4.39)	-3.37 (-6.19 to -0.55)	-0.79 (-1.03 to -0.55)	-0.38 (-0.90 to 0.14)	3,851 (2,553 to 5,144)

^aThe 95% UIs on nutrient intake, GHG emissions and cost of diets calculated as ± 1.96 multiplied by the standard error of the indicator per capita. The 95% UIs on prevented chronic disease cases are estimated by taking the bottom 2.5% and top 97.5% of the distribution of prevented cases.

a statistically significant difference in cost savings between the most deprived quintile and the least deprived quintile (Supplementary Data).

While current UK dietary guidelines recommend limiting red meat consumption to no more than 70 g per day²⁴, this remains considerably higher than recommendations in other countries that also account for environmental impacts such as the Nordic Nutrition recommendations of 50 g per day²⁵. Our results suggest that reducing red meat consumption to no more than 60 g per day will meet the 2030 CCC recommendation and provide benefits to population health and the environment while having little impact on food expenditure or nutrient intake.

Self-reported dietary intake is typically underreported, with the most recent doubly labelled water substudy of the UK National Diet and Nutrition Survey finding energy intake to be underreported by 33–41%²⁶. Absolute values for nutrient intake, environmental outcomes and cost of diets should therefore be considered lower bounds (that is, they are conservative estimates). As the change in these outcomes is not affected by baseline intake, we focus on the change relative to baseline for each pathway as the primary results. We did not estimate the proportion of the population with nutrient intakes below the dietary reference values, as these proportions are likely to be overestimated when energy and, hence, nutrient intakes are underreported. Our results reflect impacts on nutrient intake and do not take into account bioavailability, which is influenced by many factors not measured in SHeS such as an individual's micronutrient status and genetics. Future research could explore how the bioavailability of iron

and zinc may vary under different meat and dairy reduction pathways. The choice of substitutes was largely guided by existing dietary goals in Scotland, for example, to increase the consumption of vegetables and oily fish. However, future work could explore other nutrient-rich substitutes, such as mussels or nuts. Furthermore, the relative risks used for estimating impacts on chronic diseases were from meta-analyses that aimed to estimate the independent impact of unprocessed and processed red meat consumption^{27,28} or dairy consumption²⁹. We did not estimate the impacts of targeted replacements of meat and dairy on chronic disease incidence because dose–response relative risk associations for targeted replacements of meat and dairy are scarce. However, we performed a supplementary analysis to determine the relative impact of caloric reduction on disease prevention by comparing the prevented cases with simulations assuming isocaloric substitution, finding that the caloric reductions were the primary contributor to prevented cases for most health outcomes (Supplementary Tables 11 and 12). Our estimates for prevented all-cause mortalities are probably conservative due to the association between unprocessed and processed red meat intake and the risk of other health outcomes such as several cancers^{4,30}.

Adopting the CCC recommendations to reduce both meat and dairy is likely to have considerable benefits in terms of environmental impacts and public health, with limited impact on nutrient intake or household budgets, particularly if red meat is replaced with plant-based alternatives or eggs. Regulations to ensure consistent fortification of

plant-based dairy alternatives with calcium and iodine should be considered given that milk and milk products are an important source of these nutrients together with the heterogeneity in nutrient content of plant-based dairy alternatives available in the UK^{18,31}. As a next step, work is needed to understand what levers are available at the local and national level to reduce red meat consumption while simultaneously promoting the consumption of healthy alternatives³². The Good Food Nation (Scotland) Act 2022³³ and forthcoming good food nation plans represent an opportunity to adopt measures to accelerate progress towards the CCC dietary recommendations and Scottish Dietary Goals. Current rates of decline in red meat consumption across the UK are not sufficient to meet a 20% decline in all meat by 2030³⁴. Policies such as the sugary drinks levy have proven to be effective at shifting population intakes in the UK³⁵ and could be considered in the context of red meat. Reducing the price of plant-based meat alternatives along with regulations to ensure they are nutritionally appropriate substitutes could also facilitate behaviour change^{19,36}. Additional fiscal measures could include value-added tax (VAT) reform by increasing VAT on meat and dairy products (meat and dairy are currently VAT exempt³⁷) while subsidizing alternatives³⁸. Future work could incorporate demand system modelling to assess the impact of price changes, including those due to fiscal reform or following geopolitical or environmental change.

Given that consumption of red meat in the Scottish context is highest on Sundays, red meat is largely purchased at supermarkets and beef dishes and sandwiches are the main contributors among high consumers¹⁹, modifying traditional meat-centric dishes and sandwiches could be an effective place to start. Adopting the CCC recommendations is a necessary first step, but achieving population-level change will require policies that make healthy plant-based foods widely available and a more desirable, convenient and affordable choice than red meat.

Methods

Nutrient intake

The average daily nutrient intake of all respondents that completed at least 1 day of dietary recall ($n = 3,447$) from the 2021 round of SHeS was computed to determine baseline intake. Most of the sample (88.3%) provided 2 days of dietary recall data. We evaluated intake of all 54 nutrients included in the UK nutrient databank³⁹. Nutritional supplements were excluded from the analysis. The meat and dairy content of all food items were obtained using the Food Standards Agency Recipe database⁴⁰ and the UK nutrient databank³⁹, which contains both the ingredients in each reported food item and the nutrient content per 100 g of both the total food item and each respective ingredient³⁹. Data on the grams of each dairy food group in composite food items were not available in the UK nutrient databank³⁹; these data were obtained from a separate analysis, published elsewhere⁴¹.

The 20% reduction in dairy included reductions of both non-composite dairy items (for example, milk) and items that included dairy as an ingredient (for example, lasagne). For non-composite items, the gram weight of the item was reduced by 20%, while for composite items, the 20% reduction was applied to gram weight of each dairy ingredient. Similarly, in the CCC pathways, the total gram weight of all non-composite meat items, as well as the meat content of composite items, including white meat, was reduced by 20% and 35%, respectively. In pathways where red meat intake was reduced among high consumers to meet a maximum daily intake, a sampling approach was employed to account for the different impacts on all indicators from meeting the maximum daily intake via reductions in different meat food types (Supplementary Information pp. 3, 4). As there was no *a priori* reason to favour a reduction in one red meat food group over another, we randomly sampled from combinations of reductions of each red meat food group in both composite and non-composite foods consumed by individuals above the maximum threshold (to either 70 g per day, 60 g per day or 31 g per day) in 10-g increments, plus the remainder, until the maximum daily intake was reached exactly. We ran a sensitivity analysis

to ensure the results were robust to the choice of increment size by comparing the maximum absolute difference in intake across red meat food groups in the most effective pathway with an increment size of 10 g to an increment size of 1 g, finding that the average maximum difference was 1.5 g (Supplementary Information p. 4). The associated gram weight reduction of non-composite meat items was then used to compute the impact on nutrient intake. For composite meat items, the gram weight of each meat ingredient was reduced incrementally until the maximum intake threshold was reached. This approach assumes that each meat consumer is equally likely to reduce one meat food group as another. The gram weight of the reduction of each meat and dairy ingredient was then used to calculate the associated reduction in nutrient intake using the nutrient content per gram, taken from the UK nutrient databank³⁹.

We considered gram-for-gram replacement pathways for the red meat reduction: pulses and legumes, vegetables, non-smoked oily fish, eggs, plant-based meat alternatives and, for red meat pathways, gram-for-gram replacement with poultry. With dairy, we considered gram-for-gram replacements with plant-based milks, plant-based yoghurt and plant-based solid fats. Cheese and cream were not replaced in any pathway given limited availability in the Scottish food retail environment¹⁸. The frequency of reported foods in each substituted food group in SHeS 2021 was used to derive a weighted composite substitution (Supplementary Information pp. 6–13 and Supplementary Data). For example, 50% of the reported food items in the oily fish food category consisted of the item 'Salmon, grilled or oven baked'. As such, 50% of the nutrients in the oily fish substitute consisted of the nutrient content of this item. In each pathway we computed both the absolute level of nutrient intake for each nutrient and the change in the nutrient intake compared with baseline, in the overall population and in population subgroups (sex, age group and SIMD).

Environmental outcomes and diet cost

For each pathway, the impact on four environmental indicators was assessed: GHG emissions, land use, water use and eutrophication, along with the cost of diets. As environmental impact data were not available in SHeS 2021, these data were obtained by mapping items in the UK nutrient databank to appropriate matches in foodDB^{15,16}. foodDB contains standardized environmental impacts and price data per 100 g of approximately 70,000 items available in UK-based supermarkets, derived by combining data from a large meta-analysis of life cycle assessments with an ingredient decomposition analysis^{16,42}. The stages in the life cycle assessments include agricultural production and the processing and transport of agricultural commodities but do not include post-production processing, packaging or the transport of processed commodities to retail stores. For each of the environmental impacts, each food in foodDB has a distribution of possible measures based on Monte Carlo analyses where region and production method for the ingredients are allowed to vary. We use the median value from these distributions for our point estimates. The environmental impact and cost of each UK nutrient databank item per 100 g was calculated by averaging the median impacts and costs of all foodDB items that were matched to each item in the UK nutrient databank. Each of the matches between the UK nutrient databank and foodDB items was manually verified by members of the research team. The total environmental impact and diet costs were calculated by multiplying the environmental impact and cost per gram by the gram weight of each consumed item, before summing over all items and dividing by the number of days of recall. The subsequent impact in each simulation pathway followed the same approach as estimating the change in nutrient intake. To estimate the population-level environmental impacts after adjusting for underreporting, we calculated the impact per calorie for each individual based on the self-reported data and multiplied this quantity by the reported gap in calories, based on their age and sex (Supplementary Information p. 18). This was then added to their individual impact based on self-reported

data, before summing these adjusted impacts over the entire population to obtain the final estimates for population-level environmental impact.

Chronic disease, mortality and obesity

Data on demographics, health status and dietary intake were used as input to a previously developed microsimulation model, which was adapted to SHeS 2021 to estimate prevented cases of type 2 diabetes, cardiovascular disease, all-cause mortality and population average BMI⁴³. In the case of type 2 diabetes and cardiovascular disease, pre-existing disease risk models^{44,45} were used to predict baseline disease risk in the absence of dietary data, before being multiplied by a relative risk associated with their unprocessed red meat intake, processed red meat intake and total dairy intake taken from meta-analyses in the case of diabetes^{27,29} and a large-cohort study for cardiovascular disease²⁸. Incidence was then estimated by multiplying each individual's disease risk by their sample weight scaled to be representative of the population size, before summing the results over all respondents. In instances where the incidence estimates did not match the observed incidence in a demographic group, the risk was calibrated to match that observed in the first simulation year. At the end of each simulation year, disease risk factors such as age and BMI were updated to calculate the updated risk for subsequent years. The dietary change was assumed to happen in the first year and remain fixed for the following 10 years.

Mortality risk was not directly related to dietary risk factors, but rather related indirectly via change in disease status, which in turn influenced mortality risk. Baseline mortality probabilities were estimated on the basis of age and sex from 2019 national mortality statistics⁴⁶, before being multiplied by a relative risk of all-cause mortality should the individual have a chronic disease^{47,48}. The number of mortalities associated with that disease was then calculated as the original sample weight multiplied by the mortality risk, with the result then being subtracted from the original sample weight, as described elsewhere⁴³.

To estimate the impact of the reduction in meat and dairy intake on obesity, we used a pre-existing model⁴⁹ that estimates the change in body weight following a change in energy intake, accounting for other variables such as sex, resting metabolic rate and physical activity levels. The decrease in weight is then used to estimate a decrease in BMI when combined with height data in SHeS 2021 (Supplementary Information pp. 27, 28).

Uncertainty analysis

Uncertainty estimates on the health outcomes were obtained by sampling from the distributions of known sources of uncertainty in each of the 50 iterations of each pathway. Fifty iterations were chosen because the width of the 95% UIs for the health outcomes did not decrease beyond 40 iterations (Supplementary Information p. 44). Sources of uncertainty included the relative risk relations between unprocessed red meat, processed red meat, total dairy intake and chronic disease risk, the parameter posterior distributions for the systolic blood pressure, high-density lipoprotein cholesterol, total cholesterol, height and weight imputation models, and the metabolic equivalent scores for different physical activity levels. The uncertainty in nutrient intakes, environmental outcomes and costs accounts for both the survey design and, for the red meat pathways, 50 Monte Carlo iterations in which different combinations of red meat food groups (for example, beef versus sausages) were reduced to a specified maximum intake level. The uncertainty in the environmental impacts also account for the within-item uncertainty in the matching to foodDB, estimated by taking the standard deviation of the medians of each matched foodDB item. More details on the uncertainty analysis are provided in Supplementary Information pp. 18–20 and 38–44.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The Scottish Health Survey 2021 data can be obtained from the UK Data Service (<https://ukdataservice.ac.uk/>, <https://doi.org/10.5255/UKDA-SN-9048-2>). Due to legal constraints, product-level data in foodDB and the mapping between the nutrient databank and foodDB are not publicly available. Access for the purpose of replication can be requested from trisha.gordon@ndph.ox.ac.uk. Data on the estimated environmental impacts and costs for food items in the UK Nutrient Databank derived from foodDB are available via Edinburgh DataShare⁵⁰.

Code availability

All source code is available via Zenodo at <https://doi.org/10.5281/zenodo.20447123> (ref. 51), with any subsequent updates available via GitHub at https://github.com/jsfken/mSHIFT_SHeS.

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Author contributions

J.K., M.C., F.C., A.M., G.M., P.A. and L.M.J. contributed to the conception of the work. M.C. and P.S. contributed to environmental and price data acquisition. R.R., A.V., C.S., S.M.F. and M.C. reviewed and verified the underlying data. J.K. conducted the data analysis. J.K. and L.M.J. drafted the paper; all other authors contributed to revising the paper critically. All authors approved the final version of the paper.

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Competing interests

The authors declare no competing interests.

Additional information

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Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- ☐ ☒ The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
- ☒ ☐ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
- ☒ ☐ The statistical test(s) used AND whether they are one- or two-sided
Only common tests should be described solely by name; describe more complex techniques in the Methods section.
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Give P values as exact values whenever suitable.
- ☐ ☒ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- ☒ ☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- ☒ ☐ Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

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- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

The Scottish Health Survey 2021 data can be obtained from the UK Data Service (<https://ukdataservice.ac.uk/>, doi: 10.5255/UKDA-SN-9048-2). Due to legal constraints, product level data in foodDB and the mapping between the nutrient databank and foodDB are not publicly available. Access for the purpose of replication can be requested from trisha.gordon@ndph.ox.ac.uk. Data on the estimated environmental impacts and costs for food items in the UK Nutrient Databank derived from foodDB is available via Edinburgh DataShare (Reference 50).

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender	Results were broken down by the "Sex" variable in the Scottish Health Survey which records self-reported sex by the household respondent. More details on data collection in the Scottish Health Survey 2021 can be found at https://datacatalogue.ukdataservice.ac.uk/studies/study/9048#documentation
Reporting on race, ethnicity, or other socially relevant groupings	Results were broken down by Scottish Index of Multiple Deprivation quintiles to assess any differences by deprivation quintile. These data were assigned via the postcode of the respondent households. Full details on data collection in the 2021 Scottish Health Survey can be found at https://datacatalogue.ukdataservice.ac.uk/studies/study/9048#documentation
Population characteristics	See above
Recruitment	See documentation on the 2021 Scottish Health Survey: https://datacatalogue.ukdataservice.ac.uk/studies/study/9048#documentation
Ethics oversight	No ethical approval was needed for this study as all primary data on participants are publicly available.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Quantitative study
Research sample	Nationally representative survey data of adults (16+) living in Scotland in 2021.
Sampling strategy	The Scottish Health Survey ensure that the sampling is nationally representative (https://datacatalogue.ukdataservice.ac.uk/studies/study/9048#details)
Data collection	More information on the data collection methods can be found in the SHES 2021 documentation: https://datacatalogue.ukdataservice.ac.uk/studies/study/9048#documentation
Timing	Time period of data collection can be obtained in the SHES 2021 documentation: https://datacatalogue.ukdataservice.ac.uk/studies/study/9048#documentation
Data exclusions	Pregnant participants (N=16) were excluded from the health simulations as the disease risk models used in the study are not applicable to pregnant women.
Non-participation	Full details on how the Scottish Health Survey 2021 data were collected can be found at https://datacatalogue.ukdataservice.ac.uk/studies/study/9048#documentation
Randomization	Full details on how the Scottish Health Survey 2021 data were collected can be found at https://datacatalogue.ukdataservice.ac.uk/studies/study/9048#documentation

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☒	☐ Dual use research of concern
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Report on the source of all seed stocks or other plant material used. If applicable, state the seed stock centre and catalogue number. If plant specimens were collected from the field, describe the collection location, date and sampling procedures.

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Describe the methods by which all novel plant genotypes were produced. This includes those generated by transgenic approaches, gene editing, chemical/radiation-based mutagenesis and hybridization. For transgenic lines, describe the transformation method, the number of independent lines analyzed and the generation upon which experiments were performed. For gene-edited lines, describe the editor used, the endogenous sequence targeted for editing, the targeting guide RNA sequence (if applicable) and how the editor was applied.

Authentication

Describe any authentication procedures for each seed stock used or novel genotype generated. Describe any experiments used to assess the effect of a mutation and, where applicable, how potential secondary effects (e.g. second site T-DNA insertions, mosaicism, off-target gene editing) were examined.