Journal of Cleaner Production 449 (2024) 141375

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Implications and impacts of aligning regional agriculture with a healthy diet

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A R T I C L E I N F O

Handling Editor: Zhifu Mi

Keywords:
Food production systems
Healthy diets
Sustainability of agriculture
Agricultural systems model
EAT-Lancet
Environmental impact quotient

A B S T R A C T

One of the most intractable challenges currently facing agricultural systems is the need to produce sufficient food for all to enjoy a healthy balanced diet while minimising impacts to the environment. Balancing these competing goals is especially intractable because most food systems are not locally bounded. This study aims to investigate the likely impacts on production, profit and the environment that result from aligning food systems to a healthy diet, as defined by EAT-Lancet. For this, we consider two distinct areas of the UK, one in East Anglia and the other in South Wales. These two regions reflect different ecosystems and therefore differing specialisations in UK agriculture. We used the Rothamsted Landscape Model (a detailed agroecosystems process-based model) to predict soil carbon dynamics, nutrient flows and crop production for the dominant crops grown in these regions, and the IPCC inventory models to estimate emissions from six livestock systems. Two scenarios were considered, one in which the study regions had to meet healthy diet requirements independently of each other and another in which they could do so collectively. To map their production to healthy diets, both study areas require increases in the production of plant proteins and reductions in the production of red meat. While changes in production can feed more people a healthy diet compared to the business-as-usual state, the overall calories produced reduces dramatically. Emissions and leaching decrease under the healthy diet scenarios and pesticide impacts remain largely unchanged. We show that local infrastructure and environment have a bearing on how "localised" food systems can be without running into substantial constraints. Whilst isolation of the farming system to a regional level, as explored here, is unlikely to be practical, we nevertheless demonstrate that aligning agricultural production towards healthier diets can generate food systems with many associated benefits in terms of agroecosystems' health and resilience to shocks in the food supply chain.

1. Introduction

Projections suggest that food production must increase by approximately 50% by 2050 (Van Dijk et al., 2021) to meet the demands of a growing population, and there is great focus on how we can do this while at the same time reducing the impacts of agriculture on the environment. Particular attention is given to issues of: land use change, whereby natural ecosystems are converted to agriculture (Grau and Aide, 2008; Tilman et al., 2011; Mladenoff et al., 2016); increasing agricultural production while minimising associated water pollution and greenhouse gas emissions (Vitousek et al., 1997; Carpenter et al., 1998; Crippa et al., 2021); and the use of pesticides, which play an essential role in crop protection, but often have negative impacts on non-target organisms (EFSA Panel on Plant Protection Products and their Residues, 2014; Serrão et al., 2022). Many arguments about the sustainability of agriculture consider the role of livestock systems, which on one hand are

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https://doi.org/10.1016/j.jclepro.2024.141375
Received 14 July 2023; Received in revised form 11 January 2024; Accepted 19 February 2024
Available online 5 March 2024

seen as substantially more polluting than more plant-based systems, but on the other hand provide essential micronutrients more efficiently on a per ha basis (Adesogan et al., 2020).

There is increasing concern that our food system is not delivering healthy diets (Global Panel on Agriculture and Food Systems for Nutrition, 2016; Dimbleby, 2020; Dong et al., 2022). In middle- and high-income countries, a shift towards ultra-processed foods provides calories without sufficient nutrient intake, increasing the likelihood of obesity and malnutrition (Dietz, 2017). Indeed, in high-income English-speaking countries and northwest Europe average body-mass index is increasing and associated non-communicable diseases are on the rise (Dietz, 2017). These include cardiovascular disease, diabetes, and cancer (Nyberg et al., 2018); all of which have serious implications on life expectancy and absorb healthcare resources (Specchia et al., 2014). In 2002 the combined direct and indirect effects of obesity for the 15 member states of the EU were estimated to be 33 billion euros per year (Fry and Finley, 2005), and more recently Public Health England (2017) reported that obesity costs wider society 27 billion pounds in England alone. The food system and agriculture must deliver much more than simply calories; they must deliver the correct balance of foods to underpin the health and well-being of populations.

The literature suggests that healthier diets have a lower environmental footprint than less healthy diets (Global Panel on Agriculture and Food Systems for Nutrition, 2016; Rockström et al., 2016; Willett et al., 2019). There is therefore a potential to produce synergies from aligning production with a healthy diet and applying sustainability measures. In 2019, the EAT-Lancet Commission published a report that established practical targets to guide transformation to a healthier more sustainable food system (Willett et al., 2019). They defined a so-called “safe operating space for food systems” where healthy and sustainable diets can be achieved while accepting that there are large uncertainties associated with quantifying the health and environmental impacts of the food system. Key metrics for health include macronutrient intake and calories, but a diversity of plant-based foods is emphasised alongside small amounts of animal-sourced foods, acknowledging the important role diversity and animal-sourced foods can play in micronutrient delivery.

Given that production leads to patterns of availability, price and distribution of food commodities (Hawkesworth et al., 2010; Harris et al., 2023), the composition of food types produced should align with that required for a healthy diet. Aligning production with a healthy diet is challenging, however, because most food systems are not locally bound. The UK, like many mid- and high-income countries, sources its food from across the globe, producing just over half of the food consumed by the population. There are many social and economic benefits associated with global food systems, not least that diversity of sourcing confers resilience to any isolated shocks that might affect one part of the food system. Likewise, producing food locally also protects from shocks abroad (Global Food Security, 2023). Food production should therefore be aligned with healthy diets at scales finer than the global system to ensure resilience. The relationships between dietary intake patterns and both health and environmental outcomes have been studied from country to global scales using life cycle analysis (LCA; Nelson et al., 2016 and references therein). These studies tend to focus on impacts in terms of greenhouse gas emissions across the whole production system, and land use. To our knowledge, none have considered the implications or feasibility of agriculture aligning to a healthy diet at finer scales, such as regional, nor do they consider the impact of dietary change on broader ranges of pollutants from agriculture such as nutrient leaching and pesticide impacts.

Here we focus our attention on two regions in the UK, one in East Anglia and the other in South Wales. We examine, through modelling, aligning agricultural production with a healthy diet. The study regions represent two diverse agricultural systems within the UK. East Anglia has a largely flat landscape, well suited to arable and horticultural production systems with relatively limited livestock production, whereas South Wales is dominated by livestock systems, particularly in upland areas where crop production is not practical. These two regions reflect the specialisation in UK agriculture that has evolved since the late 1940s (Robinson and Sutherland, 2002), and as such offer two scales at which we can investigate the potential for aligning agricultural production with a healthy diet, first at the scale of each region individually and second at the scale of the combined regions, so allowing specialisation to give additional flexibility in how we align the diet. At these two scales, we investigate the impacts of aligning production to a healthy diet. We consider the livestock systems and crop types that would be required —accounting for environmental (climate, topography, and soil) and infrastructural constraints — and estimate their associated impacts compared with a business-as-usual (BAU) scenario. We consider nutritional delivery in terms of dietary balance and calories, greenhouse gas emissions (GHG), nitrogen leaching, pesticide impacts in terms of Environmental Impact Quotients (EIQs; Kovach et al., 1992) and farm-gate profit. We discuss the trade-offs associated with these outcomes across the two scales and discuss the implications of our analysis.

2. Materials and methods

2.1. Study area description

Agriculture varies across the UK, with a greater proportion of arable systems in the east and a greater proportion of pastoral or mixed systems in the west. We therefore selected one of our study regions to be in East Anglia, and the other in South Wales. We refer to these study areas as EAS and SWS, respectively, to differentiate from their encompassing regions. Both study areas were approximately 5000 km^2 (Fig. 1). The SWS was chosen due to the mix of agriculture that is present in the region. It is bounded in the east by the Wales-England border and is otherwise defined to include some of the upland grasslands in the north of the region and some arable land which is concentrated in the south and east of the region. The EAS was chosen due to its diverse portfolio of crops including sugar beet, which is possible due to the nearby sugar beet factories in Bury St. Edmunds and Wissington. Together, these two regions represent a large proportion of the types of agriculture found in the UK.

East Anglia has an average minimum temperature of 6.19 °C and an average maximum temperature of 13.78 °C. South Wales has similar temperatures (an average minimum temperature of 7.13 °C and an average maximum of 13.67 °C) but is wetter (964 mm year^{-1}) than East Anglia (626 mm year^{-1}). To account for the variability of the soil, we partitioned each study region into three zones according to soil texture. We assigned these as low, medium, and high clay soils. The values used for texture, bulk density, soil organic carbon (SOC) and pH for each zone can be found in the Electronic Supplementary Material (ESM Table A1). We ran the model for each soil zone and recombined the results to reflect the relative proportions of zone types observed in the region (see ESM Table A1).

2.2. Rothamsted Landscape Model (RLM)

The Rothamsted Landscape Model (Coleman et al., 2017; Milne et al., 2020) is a process-based model that simulates soil processes (including soil organic matter, soil nutrients and water dynamics), livestock production, crop growth and yield of cereals (wheat, barley, and oats), oilseed rape, field beans, sugar beet, forage maize, potato, onions, and grass. The crop model uses daily weather variables to predict canopy development and yield. The weather data required to run the model are minimum and maximum temperature, rainfall, solar radiation, vapour pressure and wind speed. Crop yield, nutrient losses through drainage, leaching and emissions, and changes in soil carbon are quantified. The model components are based on well-established existing models such as RothC (Coleman and Jenkinson, 1996), LINTUL (Wolf, 2012), SUCROS (van Laar et al., 1997), and Century (Parton et al., 1994), with water movement as described by Addiscott and

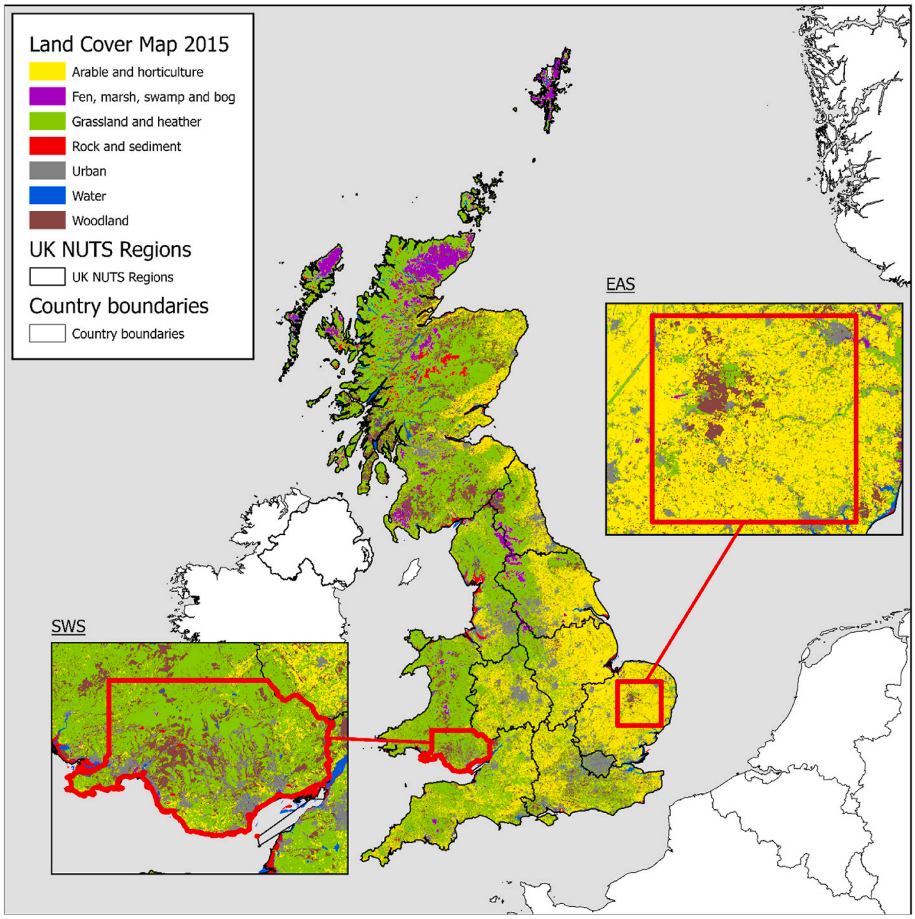

Fig. 1. A map of the UK showing the locations of the study regions (indicated by the red boundaries). Also plotted is the 2015 UKCEH Land Cover Map (Rowland et al., 2017) indicating land use in Great Britain and UK NUTS regions (Nomenclature of territorial units for statistics; Eurostat, 2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Metrics computed for the scenario analysis.

Metric	Description
Calories produced (average kcal year^{-1} study region^{-1})	Estimated farm gate production is converted to calories that reach the plate by accounting for losses associated with waste, milling, and holding-back seed for planting
Dietary balance	The composition of diet according to food groups is compared to the EAT Lancet dietary guidance
Greenhouse gas emissions (average t-CO_2 year^{-1} study region^{-1})	Estimates of nitrous oxide and methane emissions from agriculture are estimated and converted to CO_2 equivalents
Nitrogen leaching (average t-N year^{-1} study region^{-1})	Estimates of leaching associated with fertiliser and manure
Environmental Impact Quotient (EIQ) (average EIQ score year^{-1} study region^{-1})	EIQs for groundwater, fish, birds, bees, and beneficial arthropods, taking account of the hazard (ecotoxicology endpoints) and risk (persistence in plant/soil/water) (Kovach et al., 1992)
Farm profit (average £ year^{-1} study region^{-1})	Based on yield estimates, crop/livestock prices and variable costs (e.g. fertiliser, pesticide, feed costs).

Whitmore (1991) and Van Ittersum et al. (2003). This model was previously validated by Coleman et al. (2017) and Hassall et al. (2022).

2.2.1. Simulated crop sequences and management

Farmers use crop rotations to reduce the risk of pests and disease and to maintain soil fertility. The RLM uses a crop sequence generator (Sharp et al., 2021) to produce plausible sequences of crops that comply with agronomic best practice, e.g. to limit growing potatoes to once every four years. The sequences that are generated accord with the expected proportion of each crop grown in each region. For the BAU states (i.e. what is currently observed in those regions) the crop proportions are derived from 2015 to 2018 data from the Land Cover: Plus Crops dataset (UKCEH, 2007). The crops that are classified within this dataset are wheat (winter and spring), barley (winter and spring), potatoes, oilseed rape, maize, field beans, sugar beet and “other”. We used regional crop statistics to determine likely crops in the “other” category for each region (DEFRA, 2019; Welsh Government, 2019). The dominant crops in the landscape could all be simulated with our model. These included those listed above as well as oats and peas. For more minor crops (soft fruit, top fruit, and vegetables) we assumed a proxy by simulating a similar crop in the model (to maintain soil dynamics) but used national statistics to inform yield (see ESM Table D1) and associated emissions (Brown et al., 2022). As there were no measures of interannual variation in yields for these minor crops, we assumed none. We calculated profit over variable costs associated with each crop using crop price, fertiliser, and pesticide costs from Redman and Nix (2020).

Crop sowing dates and fertiliser application rates and timing were taken from national statistics (DEFRA, 2018; Redman and Nix, 2018). The values used by the model are summarised in ESM Table A2. Pesticide use associated with each crop was derived from the Pesticide Usage Survey (Ridley et al., 2020), which is an extensive survey done to determine the amount of each pesticide product applied by farmers nationally. In discussion with an agronomic expert, we determined from these data the most likely typical program that a single farmer might

Table 2
Caloric daily intake according to food group as recommended by EAT-Lancet (Willett et al., 2019).

		Caloric intake kcal per day	Percentages
Whole grains	Rice, wheat, corn and other	811	32
Tubers or starchy vegetables	Potatoes and cassava	39	2
Vegetables	All vegetables	78	3
Fruits	All fruits	126	5
Dairy foods	Whole milk or equivalents	153	6
Protein sources	Beef, lamb, or pork	30	1
	Chicken and other poultry	62	2
	Eggs	19	1
	Fish[a]	40	2
	Legumes	284	11
	Nuts	291	12
Added fats	Unsaturated Oils	354	14
	Saturated Oils	96	4
Added sugars	All sugars	120	5
	Total kcal per day	**2503**	

[a] In our analysis we focus on UK agriculture and so exclude fish protein. Nuts were grouped with legumes as plant proteins, which were modelled by peas and beans.

apply in each crop (avoiding the use of multiple products of the same type on a single crop; Richard Hull pers. comm.). The process-based model calculates nutrient losses through drainage and leaching, and emissions of greenhouse gases. For pesticide impacts, we followed the methods established by Kovach et al. (1992) to calculate EIQs for groundwater, fish, birds, bees, and beneficial arthropods, considering both the hazard (ecotoxicology endpoints) and risk (persistence in plant/soil/water) of each agrochemical applied in a standard pesticide program for each crop (Metcalfe, 2024; ESM E).

2.2.2. Simulated livestock impacts

We considered the major livestock types: cows (beef and dairy), pigs, sheep, and chickens (broilers and laying hens). The methane (CH_4) and nitrous oxide emissions (N_2O) associated with livestock as well as nitrogen (N) losses through leaching are based on the values from the UK greenhouse gas inventory (Brown et al., 2022). Taking a systems approach to our calculations, we accounted for losses associated with the whole herd or flock (e.g. for the beef system: calves, finishers, and cows), and not just those associated with the animals that enter the food system. For this, relative numbers of each life stage were derived from Redman and Nix (2020), as were stocking rates, feed requirements, production statistics (such as weight at slaughter or egg production) and variable costs (see ESM B for details). Livestock numbers for the BAU state were estimated by scaling the 2018 regional livestock numbers (DEFRA, 2022b, 2023) down from the NUTS (Nomenclature of territorial units for statistics; Eurostat, 2023) region to our study area (EAS and SWS were 25.6% and 24% the size of their corresponding NUTS region, respectively).

2.2.3. Deriving nutritional metrics from predicted yield

Not all crop produced reaches the plate. There are losses associated with waste, milling, and holding back seed for planting. Similar losses are associated with animal production systems. The estimates used for the losses between farm-gate and plate are summarised in ESM Table D2. These estimates, along with estimates of the calories per kg and yield (ESM Table D1), were then used to derive the calories per ha of human-edible food produced.

2.3. Scenarios

To assess the effect of aligning regional food production with the requirements of a healthy diet, we consider three scenarios: a (BAU) scenario and two idealised scenarios in which production was modified to align with a healthy diet. For each scenario, we calculated the profitability and environmental impacts (Table 1). The three scenarios are defined as follows:

- Business-as-usual (BAU), where production reflects current practice in each study region.
- Regional, where production was modified to align with a healthy diet at the scale of each study region individually.
- Trade, where production was modified to align with a healthy diet at the scale of the combined study regions in which we utilise some of each region's specialisation and allow excess produce to be "traded" between regions, i.e., allowing one region to grow more of a particular food group and the other to grow less but constraining the combined outputs to reflect a healthy balanced diet.

For these scenarios, we used the definition of a healthy diet provided by EAT-Lancet (Willett et al., 2019) to guide our modelling and set the areas assigned to each food group such that the calories produced were distributed among the eight food groups according to the EAT-Lancet diet (see Table 2). While the EAT-Lancet diet reports the recommended diet in terms of the requirements of an adult male, from analysing the recommended dietary requirements of children from the ages of four to eighteen (Public Health England, 2016) we find that while the recommended total calories vary, the relative proportions of macronutrients required are broadly similar across age and gender. The healthy diet scenarios described here are therefore valid across many demographics. We assigned the modelled crops and livestock to these food groups according to ESM Table C1 which was derived by estimating relative BAU areas. Of note here is that there are no uplands in EAS and that it is currently not feasible to grow sugar beet in SWS due to processing constraints. Consequently, in the Regional scenario, there is no 'added sugar' produced in SWS. To maintain the concepts of a closed system in our scenarios, we assume that the feed associated with each livestock type was produced within the same region (see ESM B for example calculations). The exception to this is with livestock that grazes in the uplands of SWS. Here we calculate the area required to produce the feed needed to support upland livestock and set aside that area in the SWS lowlands. Further, due to the large number of livestock reared in SWS under our BAU scenario, we assumed that some feed is imported.

To calculate the impacts of each scenario, we ran the models using weather data generated from the LARS-WG weather generator trained on daily observed weather data from local weather stations from 1981 to 2010 (Harkness et al., 2020) to produce 300 realisations of annual weather for each site. A summary of the weather variables generated is available in ESM Table A3. To capture the composition of crops in the landscape, we used the crop sequence generator and ran 500 stochastic realisations per weather set and soil type. We weighted the outputs for a given soil type according to the proportion of that soil type in the study area. We took the mean across stochastic realisations to calculate the expected values for any given year. We report the expected values with standard deviation across years to indicate variability in the outputs due to climate.

3. Results

3.1. Crop and livestock areas

In both study areas, for both of our healthy diet scenarios, we observed a decrease in the areas allocated to the production of starchy vegetables and red meat and an increase in the areas allocated to vegetable oils, fruit, chicken, and plant proteins compared with BAU

Table 3
Land areas (ha) for each food group described in the EAT-Lancet diet for each of our three scenarios: “Business-as-usual” (BAU), “Regional” and “Trade”.

Location of study area	Food Group	BAU	Regional	Trade
East Anglia (EAS)	Whole Grain	154 719	34 348	34 795
	Starchy Veg.	14 712	1223	1239
	Plant Protein	15 224	204 443	207 104
	Added Fat (Oil Seeds)	37 127	46 131	46 732
	Added Sugar	26 351	15 660	21 603
	Vegetables	24 663	5530	5602
	Fruit	3582	9983	10 113
	Dairy [a]	5793	21 559	21 840
	Red Meat (lowland) [a]	79 293	10 425	0
	Red Meat (upland) [a]	0	0	0
	Poultry [a]	3805	15 980	16 188
	Eggs [a]	5189	5176	5244
	EAS (total)	**370 459**	**370 459**	**370 459**
South Wales (SWS)	Whole Grain	7321	8475	8250
	Starchy Veg.	1644	464	451
	Plant Protein	227	75 461	73 464
	Added Fat (Oil Seeds)	1599	17 364	16 904
	Added Sugar	0	0	0
	Vegetables	892	2086	2030
	Fruit	90	3573	3478
	Dairy [a]	100 211 †	8115	7900
	Red Meat (lowland) [a]	57 278 †	0	0
	Red Meat (upland) (grazing)	93 956	15 558	57 018
	(feed – lowland)	7408 †	1227	4496
	Poultry [a]	635 †	6015	5856
	Eggs [a]	6648 †	1948	1897
	SWS (total)	**277 909**	**140 285**	**181 745**
	SWS (lowland + imported feed)	**183 953**	**124 727**	**124 727**
	SWS (lowland)	**124 727**	**124 727**	**124 727**
Total (lowland)		**495 186**	**495 186**	**495 186**
Total (lowland + upland)		**589 142**	**510 744**	**552 205**
Total (including imported feed)		**648 368**	**510 744**	**552 205**

† Partly from imported feed (59 226ha; 93%).
[a] Both the grazing area required and the estimated amount of land required to produce the feed.

(Table 3). Dairy was reduced in SWS but increased in EAS, and both vegetables and whole grain was reduced in EAS but increased in SWS. There was a net decrease in all three of these food group areas across both study regions. There was little change in the area assigned to EAS eggs across scenarios.

In the trade scenario, all red meat production in EAS was moved to the SWS uplands. Even then, the area dedicated to red meat in SWS was less than that under BAU. This is despite the SWS upland area providing fewer calories per ha than the EAS red meat area (ESM Fig. F1) due to 74% of an EAS red meat ha being dedicated to pork (ESM Table C1), which provides more calories per ha than beef or lamb.

3.2. Nutritional delivery

The expected calories produced under the Trade scenario are slightly greater than those produced under Regional (Fig. 2a). This is due to the red meat production being shifted from EAS in the Regional scenario to SWS uplands in the Trade scenario where it is not possible to grow crops. This allows a greater ceiling for combined production. While this slightly reduces the edible calories produced in SWS due to additional land being assigned in the lowlands to produce animal feed, this is outweighed by the increase in food production in EAS as the land previously assigned to rear and support livestock is distributed across the other food groups. Aligned with the observations on production areas, the largest reduction in calories is associated with whole grains and the largest increase is associated with plant proteins (Fig. 2b).

Table 4 shows, for each food group, the number of people fed by dividing the number of calories produced by the number of calories required per person according to the EAT-Lancet report. This calculation assumes an intake of 2500 kcal person^{-1} day^{-1} as per the EAT-Lancet report (Willett et al., 2019) which is the calorie intake recommended for an adult male. Although other demographic groups would require a lower intake of calories the choice of value here is arbitrary. The effect of lowering the value will increase the number of people fed reported but will do so for all scenarios. The qualitative effect will therefore remain unchanged. Averaging across the food groups we see that the number of people fed falls from 6.97 million in the BAU scenario to around 2.36 million in the healthy eating scenarios. The BAU value is slightly inflated however due to the animal feed that is imported under the scenario. This imported feed requires an additional 59 226 ha outside our study area to produce, which could feed approximately another 280 000 people on an EAT-Lancet-compliant diet. Nor, importantly, does it account for how balanced the diet is as the BAU scenario is dominated by whole grains, starchy vegetables, vegetables, dairy and red meat. By instead considering the number of people that can be fed an EAT-Lancet-compliant diet we find there are 129 519 in the BAU scenario, 1 713 202 in the Regional scenario, and 2 363 283 in the Trade scenario.

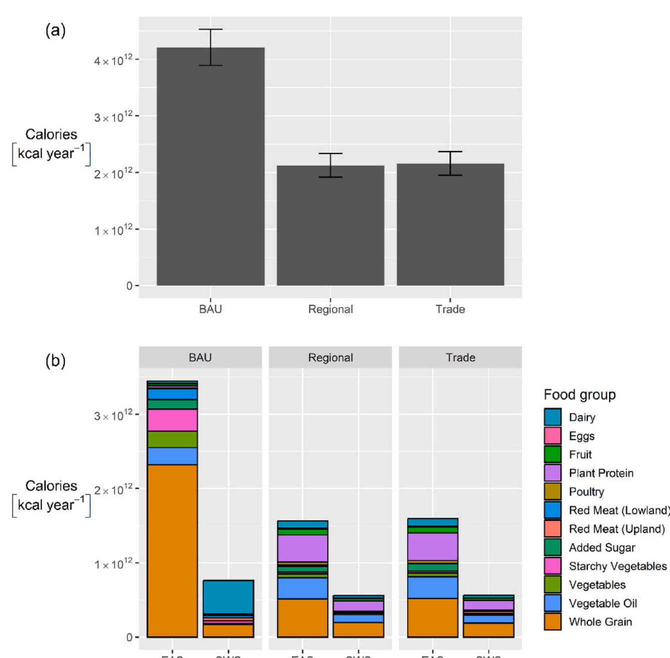

Fig. 2. Calories produced, by: (a) scenario, with the vertical bar indicating the standard deviation across modelled years; (b) scenario, broken down according to study area and food group. The order of the crops in each bar is the same as that in the legend.

Table 4
People fed. Calculated by dividing the average annual calories produced for each food group by the study regions by the numbers of calories of each food group required according to EAT-Lancet's planetary health diet, which assumes an intake of 2500 kcal person^{-1} day^{-1} (Willett et al., 2019).

	BAU	Regional	Trade
Dairy	8 423 472	2 358 051	2 363 284
Eggs	3 917 919	2 358 052	2 363 284
Fat	1 438 182	2 358 051	2 363 284
Fruit	630 948	2 358 051	2 363 284
Plant protein	129 520	2 358 051	2 363 284
Poultry	475 982	2 358 051	2 363 284
Red meat	19 676 557	2 358 051	2 363 284
Starchy vegetables	22 897 132	2 358 051	2 363 284
Added sugar	2 882 797	1 713 202	2 363 284
Vegetables	7 916 492	2 358 051	2 363 284
Whole grain	8 274 122	2 358 051	2 363 284

3.3. Greenhouse gas emissions

In both healthy food scenarios, greenhouse gas (GHG) emissions are reduced compared with BAU (Fig. 3a). However, on a study region basis, we see that the emissions from the EAS reduce only slightly, whereas emissions from SWS reduce substantially in line with the reduction in livestock. Emissions under the Trade scenario are greater than those under the Regional. This is because the red meat production is moved to the SWS uplands resulting in more food being grown across the two regions, and a move away from pigs towards more cattle and sheep. This change in livestock mix increases emissions in two ways: it has higher emissions per hectare, and requires more hectares to produce the same number of calories (ESM Fig. F1). Another notable change between the BAU and healthy diet scenarios is the increase in emissions from plant proteins which reflects the significant proportion of land being assigned to the food group. When considered on a per-calorie basis, emissions are still lower under the healthy diet scenarios compared with the BAU, but the relative differences are far smaller (ESM Fig. F2).

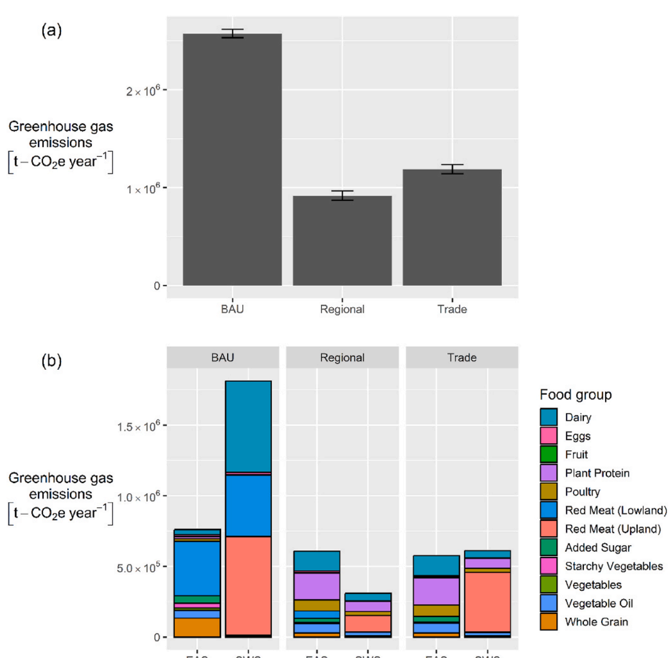

Fig. 3. Greenhouse gas emissions, by: (a) scenario, with the vertical bar indicating the standard deviation across modelled years; (b) scenario, broken down according to study area and food group. The order of the crops in each bar is the same as that in the legend.

3.4. Nitrogen leaching

The expected amount of nitrogen that leaches is smaller under our healthy eating scenarios compared with BAU (Fig. 4a). In SWS leaching is predicted to reduce substantially under the healthy eating scenarios. This is largely driven by reductions in dairy production and lowland red meat production. As with the GHG emissions, a large proportion of leaching in both healthy diet scenarios comes from plant proteins on account of the large area being dedicated to growing that food group.

3.5. Pesticide impacts

Compared with BAU, total EIQ decreased slightly under the Regional scenario (−0.7%) and increased slightly under the Trade scenario (+0.34%; Table 5). The largest changes related to reductions of impacts associated with cereals and dairy (as these areas decline) and increases directly related to increasing plant-based production (Fig. 5). Investigating each impact individually (Table 5 and ESM Fig. F.3 – ESM Fig. F.7), we see that the response is differential, with impacts increasing for groundwater and beneficial arthropods and reducing for other categories.

3.6. Profit

The expected profit reduced from BAU in the Regional and Trade scenarios (Fig. 6). We note however that there are large standard deviations associated with these predictions. This drop in profit particularly impacts SWS and is driven by replacing dairy systems with less profitable plant proteins.

4. Discussion

We considered two contrasting areas of the UK and determined the changes they would need to make to align agricultural production to a healthy diet (as defined by EAT-Lancet) and the associated impacts of these changes.

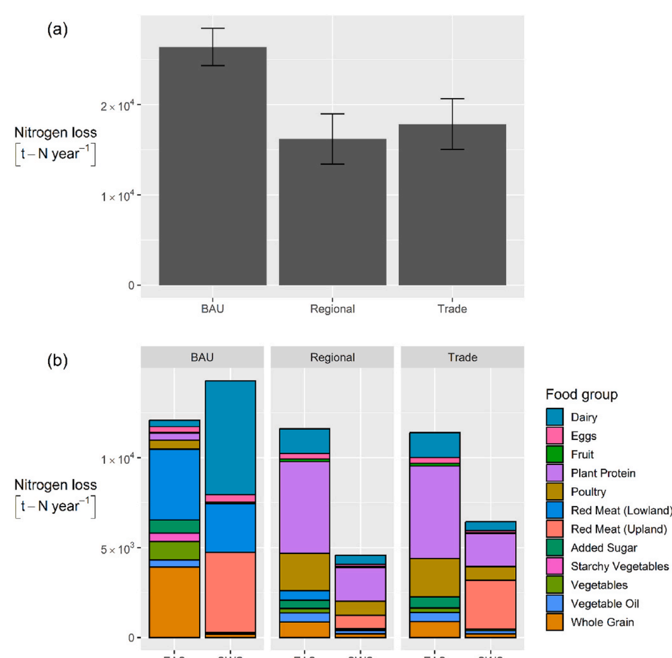

Fig. 4. Nitrogen leaching, by: (a) scenario, with the vertical bar indicating the standard deviation across modelled years; (b) scenario, broken down according to study area and food group. The order of the crops in each bar is the same as that in the legend.

Table 5
Environmental Impact Quotients (EIQ) for the Business-as-usual, Regional and Trade scenarios.

EIQ Type	BAU EIQ/10^9	Regional EIQ/10^9	Trade EIQ/10^9
Groundwater	2.06	2.53	2.57
Fish	8.03	7.69	7.77
Birds	12.52	11.77	11.9
Bees	13.19	12.61	12.84
Beneficial arthropods	28.40	29.15	29.34
Sum (EIQ_C)	**64.20**	**63.75**	**64.42**

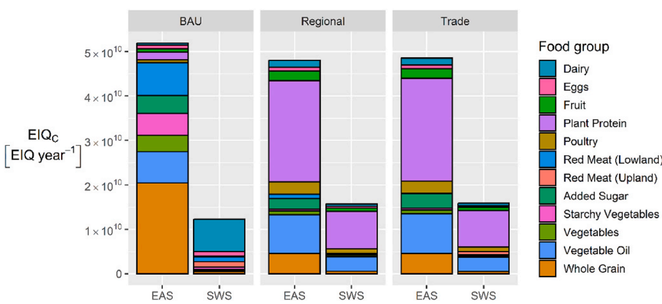

Fig. 5. Total Environmental Impact Quotient (EIQc) by scenario, broken down according to study area and food group. The order of the crops in each bar is the same as that in the legend.

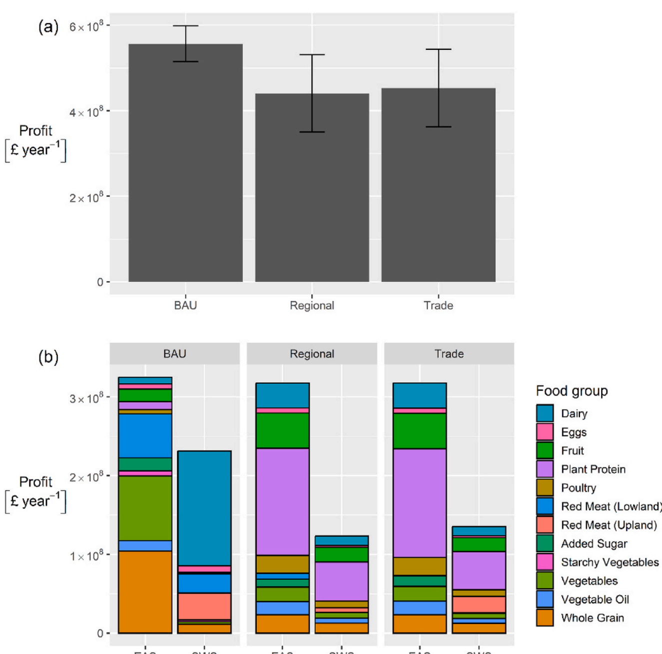

Fig. 6. Profit, by: (a) scenario, with the vertical bar indicating the standard deviation across modelled years; (b) scenario, broken down according to location of the study area and food group. The order of the crops in each bar is the same as that in the legend.

4.1. Predicted outcomes

The predominant change required by both of our study areas is to increase the production of plant proteins and reduce the production of red meat. This results in a net reduction in emissions between these two products, but environmental impacts associated with plant proteins in terms of GHG emissions and pesticide impacts are notable. While fertiliser is not applied to these crops, they are nitrogen-fixing crops and so nitrogen is still introduced to the system.

When moving from BAU to either healthy diet scenario, some land use changes were consistent across regions, such as an increase in the area allocated to producing white meat and fruit, and a reduction in the area allocated to starchy vegetables. Some changes were not consistent across regions, notably in relation to areas allocated to whole grain. This commodity is proportionally abundant in EAS under BAU and the area is reduced under each healthy diet scenario, whereas in SWS the production area increases. Conversely under our healthy diet scenarios, dairy production is reduced compared with BAU in SWS yet increases in EAS. The BAU states align with the regional specialisation that is observed across the UK in which arable and horticulture are more predominant in the east and livestock in the west. This is largely driven by the environment with grazing being more viable than cereal production in the wetter and hillier west, and cereal yields reportedly lower in the west compared with the arable east (DEFRA, 2022a). We partially captured this in our scenarios by deeming the SWS uplands to only be suitable for livestock systems and EAS to only be suitable for producing added sugar, but otherwise allowed for food groups to be assigned according to the EAT-Lancet diet while respecting each region's BAU crop mix (ESM Table C1).

When considering calories produced, the reduction in people fed under the healthy diet scenarios is substantial (Fig. 2 and Table 4). In EAS, this is driven by growing more plant proteins in place of cereal crops. In SWS, this is due to dairy production being reduced substantially and less area being under production due to a reduction in livestock production in the uplands where no other food production system is viable. However, when we consider the number of people that can be fed a balanced diet, the BAU system fairs substantially worse than our other two scenarios. In the BAU scenario plant proteins are the limiting factor. Other food groups that need to be increased to meet EAT-Lancet's recommendations are fruit, poultry, and vegetable oils. Compared to the Trade scenario, the amount of people that can be fed the EAT-Lancet diet in the Regional scenario is relatively low. In this case, the added sugar category is the limiting factor. This is due to our assumption that processing constraints make it infeasible to grow sugar beet in SWS. The other food groups in the Regional scenario are also marginally lower than in the trade scenario due to land being assigned to produce red meat in EAS. This underlines the importance of both environment and infrastructure in production systems even at the scale of the UK.

Compared with the BAU scenario, GHG emissions are reduced substantially in our two healthy diet scenarios. This is predominantly driven by reductions in livestock and dairy systems, and as a result, is more notable in SWS. Emissions under the Trade scenario are greater than those under the Regional. This is partly because livestock production in the upland areas is allocated to beef and sheep, which emit more greenhouse gases per kg of meat produced than pork (Poore and Nemecek, 2018; Brown et al., 2022). This is another example of where practical considerations associated with local environment may be driving choices that could be less environmentally sound. GHG emissions reduce substantially, but when considered in the context of calories produced the differences (although still beneficial) are marginal (see ESM Fig. F1 and ESM Fig. F2).

The environmental impact of pesticides changed little in both healthy diet scenarios compared to BAU. We assumed a standard pesticide program was applied to each crop type; however, it is possible that these typical programs would change together with changes in cropping practices.

Profitability is predicted to decrease in both our healthy diet scenarios. The largest reduction in profit seen for SWS was associated with the reduction in dairy. The dairy industry in SWS employs significant numbers of people and it is not clear that these jobs would automatically transfer to industries associated with field crops if the land-use changed from BAU to either Regional or Trade. Even if production were moved to higher-elevation sites, the nature of the work would undoubtedly differ and while livestock production might continue in this way, the need for twice-daily milking would present enormous difficulties to the Dairy industry. The largest changes in EAS were from grains or leafy vegetables to plant proteins. This change in production may affect businesses and employment in terms of fewer seasonal workers being needed to support vegetable production.

An implication of the reduction in animal production is the decrease in grain needed to feed animals. Cereals are a profitable part of the agribusiness in EAS, but it is likely to be bread-making wheat for human consumption that delivers the largest per hectare share of farm income from cereals. This is unlikely to be impacted by a reduction in animal numbers unless feed producers turn to bread rather than vegetables and so compete with existing bread wheat producers. In practice, the difference in farm types is not so specialised. The greatest impact therefore is a likely increase in risk for cereal farmers who no longer diversify grain production as widely as under BAU.

4.2. Constraints

While we consider the impacts of aligning production to a healthy diet by considering regional case studies, we do not suggest or explore self-sufficiency. We do however consider alignment of the system to a healthy diet at two scales (Regional and Trade). Compared with global systems, the scales we consider are small, but even across these two scales, we show that local infrastructure and environment have a bearing on how "localised" food systems can be. We found that Regional and Trade scenarios gave similar predictions for most outcomes except for where regional constraints made a difference. This is particularly evident for red meat production, where in our Trade scenario production moves to the SWS uplands where it is not possible to grow crops due to poor soil conditions, wet climate, more mountainous terrain and associated difficulties of getting the necessary machinery to these areas (Roberts, 2014). This shift from lowland livestock systems to upland livestock systems resulted in more land being available in the lowlands for crops, and a shift away from pigs to more cattle and sheep. Environmental conditions also affect crop production, with yields in the arable east generally outperforming yields in the wetter southwest (DEFRA, 2022a). This is thought most likely to be due to poor establishment in the wetter autumn and the advantages of farming the flatter larger fields more typical in the east of England. These factors are not captured in our model, meaning that yields associated with Wales are likely to be overestimated. Wetter conditions also mean emissions and leaching associated with fertilisers are likely to be greater in SWS, and this is predicted in our model.

Our Regional scenario was constrained by the fact that there are no sugar processing facilities near SWS, limiting the ability of that region to provide added sugars. Other infrastructural constraints not included in our analysis will also exist, making regional alignment for food systems more challenging. For example, vegetables destined for frozen food typically must be grown within a short distance of the processing plants. Arguably, environmental factors have led to more specialised systems with infrastructures designed accordingly, making reversion to more diversified and mixed systems non-trivial. Modern intensive farming has led to the necessity for capital-intensive machinery which further encourages specialisation in livestock and arable agriculture, however, reportedly at the loss of biodiversity (Robinson and Sutherland, 2002).

4.3. Motivations for change

Under the healthy diet scenarios, far fewer calories are produced compared with the BAU scenario (Fig. 2 and Table 4). This is a strong argument for specialisation, but with that comes the assumption that missing components of the diet (e.g., plant proteins and fruit) can be easily sourced globally without substantially more detriment to the environment. This is often not the case due to related food miles, but there are notable examples where imported produce is associated with a lower carbon footprint (Saunders and Barber, 2008; Ledgard et al., 2011). In recent times the fragility of relying on the global food systems for sufficient affordable food has come to the fore with both the recent COVID-19 pandemic and global security threats disrupting food supply and causing shortages (Laborde et al., 2020; Zurayk, 2020; Nchanji and Lutomia, 2021; Ben Hassen and El Bilali, 2022; Hellegers, 2022). Increasingly environmental and policy shocks have also disrupted supplies, emphasising the need for resilience of supply across scales. Specialisation may therefore pose risks globally and better alignment to healthy diets across scales should build more resilience.

Growing concerns around the impacts of intensive farming on soil health and biodiversity have led to renewed interest in more diversified rotations and mixed farming systems in the UK, with a wider shift towards more agroecological solutions (Cusworth et al., 2021). This move would arguably align better with our healthy diet scenarios, but our analysis suggests a corresponding loss of profit. A recent review and meta-analysis by Rosa-Schleich et al. (2019) accorded with this view but showed that in the longer term, diversified farming practices have the potential to lead to higher and more stable yields, increasing profitability.

Despite the infrastructural and economic challenges associated with aligning the food systems to a healthy diet across scales, there is the potential to shorten food chains and make food provenance more transparent to the consumer. There is evidence to suggest that stronger links to food provenance and preparation lead to healthier choices and improved well-being (Hansmann et al., 2020; Mills et al., 2021; Bellamy et al., 2023; Verfuerth et al., 2023). When people are linked to where their food comes from, and importantly, linked to the actors across a community-scale food system, their diets align more closely with the EAT-Lancet recommended diet. Multiple factors may drive this association. Nonetheless, Bellamy et al. (2023) found that such dietary changes, e.g. less meat, more vegetables and pulses, corresponded with a reduction in GHG emissions of almost 30%. Ultimately any changes in production systems that are not viewed as more profitable will require incentivisation. Aston et al. (2012) argued that joint consumer and producer responsibility is needed to support change, however, cost and awareness of implications are likely to be a significant factor for both groups. In their review, Piñeiro et al. (2020) found that short-term economic benefits offered a greater incentive for adoption than programmes that promoted ecological benefits alone, although one of the strongest motivations for farmers to adopt sustainable practices was the perception that these benefited their farms, the environment or both. Given this, stronger connections between farmers and consumers could also help incentivise changing production system. This connection can benefit farmers by enhancing their overall well-being through increased security, satisfaction, and pride. This is achieved by cultivating customer appreciation and providing farmers with greater autonomy to respond to consumer feedback and diverse crop demands. Jaccarini et al. (2020) found that such approaches can result in less food wasted and a greater share of profits received by farmers. Nonetheless, evidence suggests that widescale change would require appropriate policy instruments that account for the characteristics of the target farmer population, and the associated trade-offs between economic, environmental and social outcomes (Schirmer et al., 2012; Weltin and Zasada, 2018). A policy approach currently being developed for implementation, that has the potential to drive changes in what is produced, is state procurement. The Welsh Labour-Plaid Cymru cooperation agreement in Wales includes the provision of free school meals for all primary school children. Exploration continues with regard to how much of this procurement could be met by Welsh horticultural production, ensuring a market for producers and thus stimulating supply. Coupling food procurement policy with changes in agricultural policies has the potential to drive changes in the types of food produced. These policy changes include subsidy payments for full-time horticultural producers irrespective of farm size, more funding for training horticultural workers, flexible planning policies for regional food processing and distribution infrastructure, and grants for farm equipment. The National Food Strategy for England also advocates approaches to support increased consumption through regional supply chains (Dimbleby, 2021). Food policies are currently being developed across the UK creating opportunities for generating the kinds of changes proposed here, e.g. Wales's Community Food Strategy, Scotland's Good Food Nation Plan, and Northern Ireland's Food Strategy Framework.

4.4. Limitations

In this study, we demonstrate a methodology for analysing the impacts of aligning production to a healthy diet. To that end, we used the dietary recommendations from the report by the EAT-Lancet Commission (Willett et al., 2019). This report proposed a diet that would be both healthier and more sustainable. Since its publication it has received several criticisms, however. A chief concern is that the authors replace too much animal-sourced protein with plant proteins leading to potential deficiencies in micronutrients such as vitamin B12, calcium, iron and zinc (Young, 2022; Beal et al., 2023). Many other criticisms relate to the diet being defined as a "planetary health diet", e.g., that such a diet would be unaffordable for many (Adesogan et al., 2020) or that a centralised diet would be culturally destructive and cause significant job losses (Torjesen, 2019). Nonetheless, the EAT-Lancet diet continues to be a useful framework that is widely used in research about the sustainability of food systems (Tulloch et al., 2023), driving discussion of how, given these concerns, food systems could be transformed to deliver healthy and sustainable diets for all (Béné et al., 2020). For our purpose, the EAT-Lancet diet was a pragmatic choice to illustrate the effect of aligning UK agricultural production to reflect a healthier and more sustainable diet. Any future scenarios rectifying the shortfall in animal-based proteins are likely to result in outputs falling somewhere between our healthy diet and BAU scenarios.

A second limitation of our research is that we do not account for any potential improvements in diet or environmental health that could result from the introduction of new crops or the implementation of regenerative agricultural practices. For example, in our model, plant protein is simulated as beans and peas as these are commonly grown crops in the UK, however, there is scope to bring in other forms of plant protein to UK systems. For instance, there is an increasing interest in growing soybean in the UK. While this offers an alternative form of break crop with potential benefits associated with diversifying rotations, predicted yields suggest it is less viable in terms of profitability, and considerations such as access to appropriate machinery (Coleman et al., 2021) mean that it is currently unlikely to be practical for most farmers. Breeding has the potential to increase the nutritional quality of crops and animal products. Key advances have been made to increase nutrient availability in staple crops such as wheat (Wani et al., 2022). Regional diversification in cropping may lead to varying pest pressures that are not currently observed. Several studies have found that diversification in cropping practices can lead to a reduction in pest pressure (Poveda et al., 2008; Weisberger et al., 2019). Ecological intensification and an associated reduction in reliance on pesticides in UK farming could further reduce the total pesticide burden on the environment in healthy eating scenarios (Bommarco et al., 2013).

Concerning the impacts of regenerative practices, farmers are increasingly encouraged to adopt minimum tillage and cover crops to increase soil health and improve nitrogen management (Gabriel et al., 2013; Schipanski et al., 2014; Adetunji et al., 2020). Over time these strategies have proven to increase soil health, although impacts of cover crops on emissions are contested with choice of cover crop affecting emissions (Basche et al., 2014).

5. Conclusion

Aligning agricultural food production to healthy diets at sub-region scale in the UK would result in lower GHG emissions and nutrient leaching, with little change to pesticide impacts. However, this change would dramatically reduce the number of calories produced and profits are also likely to be smaller. Environmental and technical constraints mean that regional specialisation does offer benefits in terms of production and profitability. The extreme scenarios that we have explored are unlikely therefore to be practical, but a move in the direction of aligning agriculture production with healthier diets is likely to generate food systems with many associated benefits in terms of agroecosystem and human health and build in better resilience across the UK food production system.

CRediT authorship contribution statement

Ryan T. Sharp: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Angelina Sanderson Bellamy:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Adrian Clear:** Conceptualization, Funding acquisition, Software, Writing – review & editing. **Samantha Mitchell Finnigan:** Software, Writing – review & editing. **Ella Furness:** Conceptualization, Writing – review & editing. **Elliot Meador:** Conceptualization, Funding acquisition, Writing – review & editing. **Helen Metcalfe:** Formal analysis, Resources, Software, Writing – original draft, Writing – review & editing. **Susanna Mills:** Conceptualization, Funding acquisition, Writing – review & editing. **Kevin Coleman:** Formal analysis, Software. **Andrew P. Whitmore:** Software, Supervision, Writing – review & editing. **Alice E. Milne:** Conceptualization, Funding acquisition, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This research was funded by the Global Food Security "Resilience of the UK Food System Programme" with support from the Biotechnology and Biological Sciences Research Council (BBSRC), Economic and Social Research Council (ESRC), Natural Environment Research Council (NERC), and the Scottish Government [grant number BB/S014292/1]. Rothamsted Research receives strategic funding from the BBSRC. We acknowledge support from the AgZero+ [grant number NE/W005050/1] and Achieving Sustainable Agricultural Systems (ASSIST) [NE/N018125/1] Institute Strategic Programmes that are jointly funded by NERC and BBSRC.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141375.

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