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Policies for food system resilience: modelling global shocks to the UK food system

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Abstract: Resilience of the food system to a range of shocks is increasingly seen as a critical objective, alongside environmental and public health outcomes. However, no attempts to our knowledge have been made to quantify how resilient food systems are in view of extreme disturbances in global supply. This study uses a novel land use modelling approach to identify trade-offs in managing resilience of the UK food system to disruptions in the global agricultural system, under a range of policy regimes. Our approach, incorporates an elastic demand system allowing us to explore supply, demand and price dynamics in more detail than is typically used in global land use models. We find raising subsidies or trade barriers for UK production has benefits for price stability and profitability, but these policy regimes are associated with a higher environmental footprint for the average UK diet. This suggests that maintaining easy and low-cost access to global agricultural markets whilst providing environmentally-targeted support to UK production sectors may lead to increased resilience for UK household food security, and the economic viability of UK farm businesses. Our results emphasize the fragility of the food system and the need for food policy decisions to consider trade-offs between multiple objectives. The methodological approach has potential for assessing food system vulnerabilities globally.

Acknowledgements

The authors acknowledges support under the project ‘Resilience of the UK food system to Global Shocks’ (project no. BB/N020545/2) funded by the Biotechnology and Biological Sciences Research Council.

Introduction

Global food supply has become increasingly integrated in recent decades, exemplified by the global import quantity of agricultural products increasing seven-fold between 1961 and 2018 (FAOStat 2020). The UK food system is currently heavily reliant upon imports, particularly from the European Union. In 2017, 50% of the food consumed in the UK was produced domestically, with 30% imported from the EU and the remaining 20% coming from the rest of the world [1]. This dependence on global markets exposes the UK food system to the disruptions, shocks, and volatility in the global food system that arise from weather, climate, economic, and political dynamics. However, being part of a diversified and competitive global food system can provide stable supply and lower food prices [2].

Emerging pressures on the UK and global food systems include reducing environmental footprint of good supply, persistent rates of undernourishment, the double-burden of malnutrition, alongside more recent acute challenges from the Covid-19 pandemic and Brexit. With this backdrop, the resilience of food systems is an emerging topic in academic and policy realms, creating further impetus for actions that policy, industry, and consumers can take to build a food system that is able to recover and improve in response to shocks and disruptions over the short and long term.

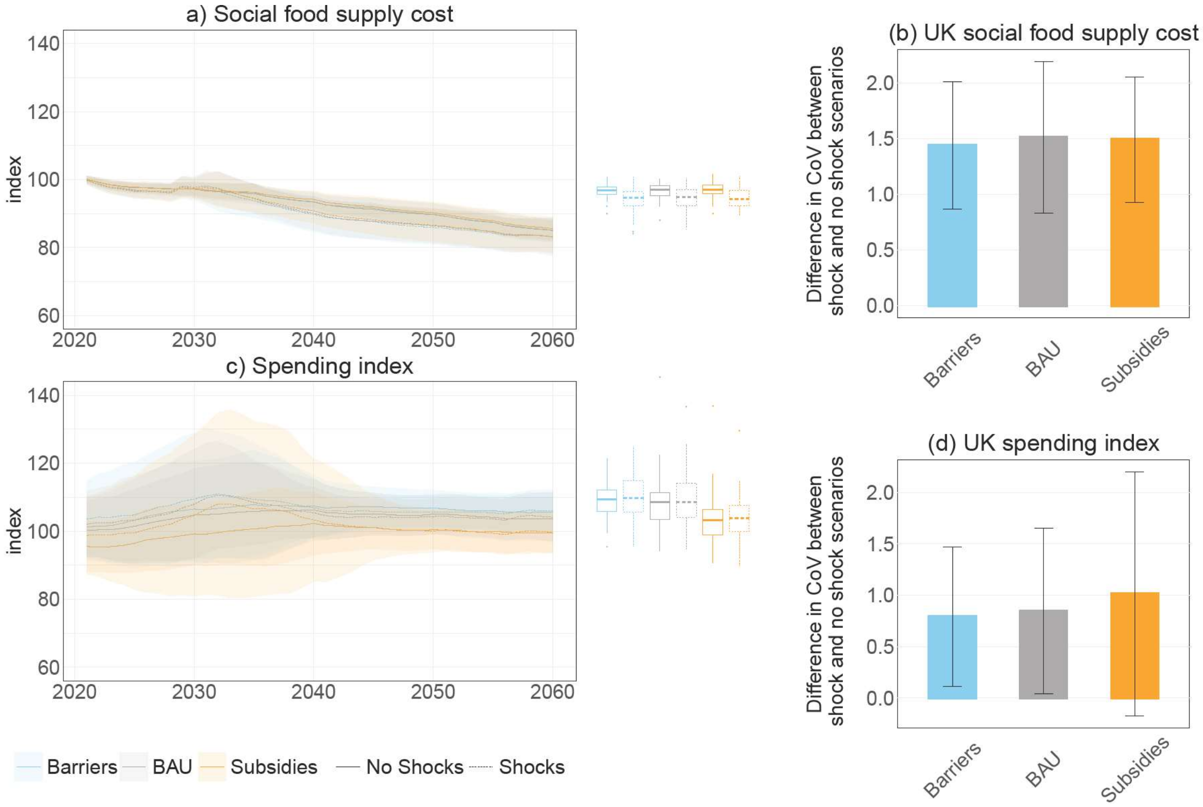
A growing number of studies have drawn on the concept of resilience from the socio-ecological systems literature to explore food systems [3–6]. This literature allows for resilience to be defined in broad terms - both at different scales and for different disciplinary approaches. The ability of an economic system to absorb shocks or to harness the opportunities from shocks is related to the institutional and policy environment. Multiple measures of social development, macroeconomic stability, microeconomic market functioning, and good governance are needed to capture all aspects of resilience of the economic system [7]. From system dynamics modelling, there have been attempts to derive quantitative measures of the resilience of a system [8]. Reviews of such quantitative approaches have concluded that there is no single way to measure system resilience, but rather a multitude of measures of different variables at different scales is needed to provide a fuller picture of the system[9]. Thus, in the approach presented here, we make use of a range of socioeconomic and environmental variables that are derived from a global model to represent the resilience of the food system in terms of (i) household food security, (ii) viability of the agricultural production sector, and (iii) environmental impact of agricultural production.

The modelling framework, LandSyMM [10,11], has its roots in economic modelling, but incorporates climate, ecosystem and crop processes to represent the food system as a socio-ecological system. This type of modelling approach has been applied to consider the long-term impacts and consequences of climate change and other future global change uncertainties [10–12]. However, little work has been done to explore the impact of temporal shocks on global and national food consumption and agricultural production systems over the medium term (0-25 years) [13]. A key innovation of LandSyMM is that it projects food demand in response to prices over the medium term, rather than just income and population changes over the long-term [14,15]. Here, we adapt LandSyMM to explore global production shocks and UK policy actions.

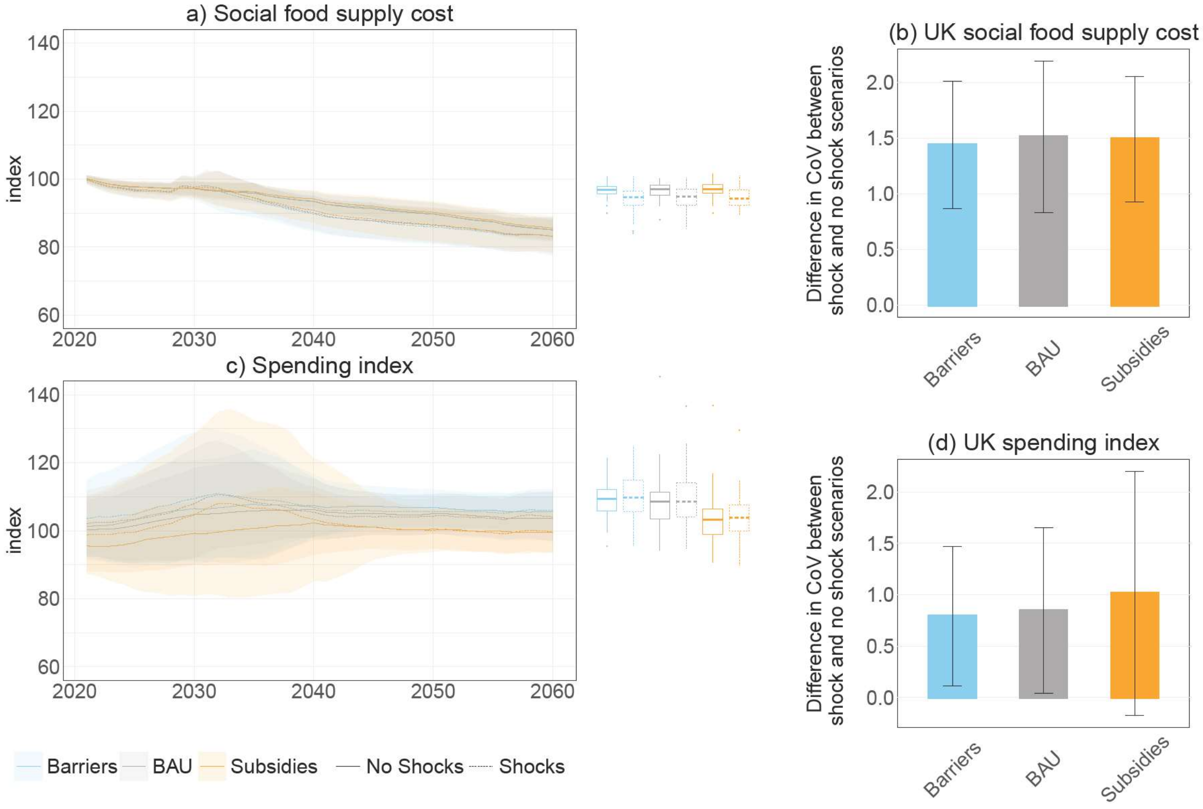
This paper considers the consequences of global shocks for diverse aspects of the UK food system, under a range of policy regimes, namely (i) *business-as-usual* (BAU) based on 2010 policy parameters, (ii) doubling of UK *trade import barriers*, and (iii) doubling of UK *agricultural subsidies*. We assess the trade-offs between the multiple objectives of a food system by exploring the potential consequences of disruptions to the production and trade of food. The paper contributes to understanding of the resilience of the UK food system, with regards to shocks and disruptions to global trade and food production. By exploring the impact of these shocks, we consider how to design UK policies that will build a resilient food system, considering multiple dimensions of resilience. With UK agricultural policy no longer determined through the European Union, the design of a UK agriculture, food and environment policy has become an increasingly pertinent issue, evidenced by initiatives such as the RSA's Food, Farming and Countryside Commission and the National Food Strategy. The findings and methodology however are also widely applicable to other nations, particularly because global shocks are unlikely to affect countries in isolation.

Results

1. Subsidies can reduce the cost of food, but all policy regimes fail to mitigate price volatility due to global shocks



Across the three simulated policy regimes, we are interested in the impact of global shocks on price volatility and the trade-off of these regimes in terms of the level of prices for society and consumers. We might expect a trade-off between policies which protect the volatility of UK prices from the global markets, and those which keep consumer spending on food affordable. The simulations show, in fact, that there is minimal difference in the impact of shocks on food costs and consumer spending volatility between different policy options (Figure **1**). Across all policy regimes, price and spending variation increases by 0.8-1.5% with shocks. For consumer spending, there is weak evidence that higher trade barriers reduce the impact of global shocks, compared to other policy regimes. However, consumer spending is significantly higher than



the business-as-usual (BAU) case when trade barriers are implemented (Figure **1**-d). The opposite is true for subsidies – they lead to lower average consumer spending compared to the BAU case. Consumer diets change very little across policy and shock scenarios, therefore consumer spending and food security in the UK continues to be directly exposed to volatility in global prices.

We find that the societal cost of food (i.e. the real economic cost of food production, rather than the cost paid by consumers) is considerably more volatile when shocks occur in global production (volatility increased by about 1.5% on average), particularly for monogastric and ruminant livestock which rely on imported feed. In contrast, there is very little impact on the volatility of consumer food spending when shocks occur (<1 % for all policy regimes). In terms of volatility, the simulated policy regimes make no significant difference to the impact of global supply shocks on UK food costs.

However, the average consumer food spending is significantly lower, compared to BAU, when subsidies are implemented. A 6.4% reduction in production costs due to higher subsidies, leads to consumer spending which is 4% lower on average. The opposite is true for increased trade barriers – these lead to average consumer spending which is higher than under BAU. The societal cost of food is unaffected by the policy regime.

To sum up, these policy options do not increase or reduce price volatility, however, subsidies reduce consumer spending on food on average, whilst increased trade barriers increase consumer spending on food. To improve food system functioning in terms of household food security, increasing agricultural subsidies seems to be the best policy. It is difficult to manage the price volatility from global shocks as the UK diet changes very little in response to policy shifts or price changes. This is explained by a continued reliance on food imports, even with increased protectionist policies.

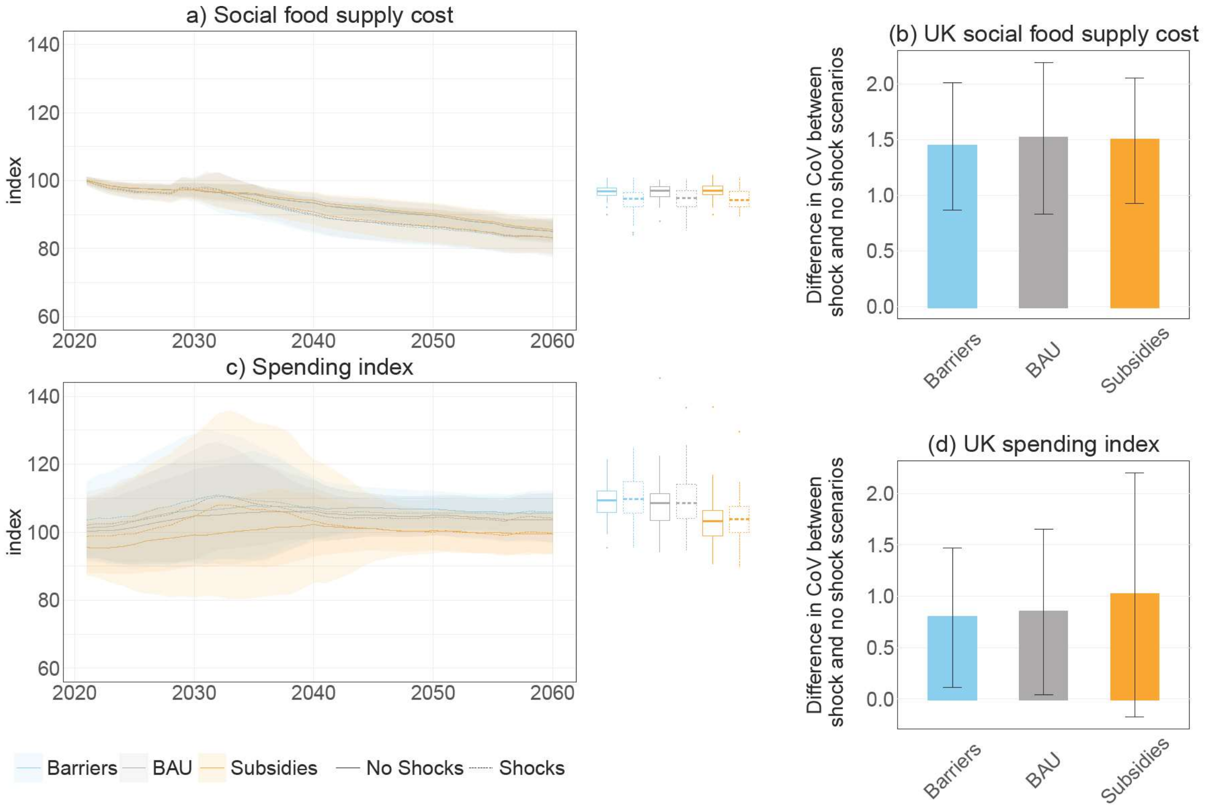


Figure 1: Cost of UK food for society & households. *Social food supply cost variable is a price index using 2010 diets as weights and reflecting the total economic cost to society of food production (i.e. subsidies are excluded). Panels a) and b) reflect level over 2020-2060 and the change in coefficient of variation between shock and non-shock scenarios. Spending index represents a daily spending index on food for the average UK diet per person, including the lower price effect due to subsidies and changes in diet. The price is an average of import price and cost of domestic production, weighted by the proportion of demand met by net imports or domestic production. Panel c) and d) show the level over 2020-2060 and the change in coefficient of variation between shock and non-shock scenarios. Confidence intervals are derived from 50 Monte Carlo simulations. The box plots in panels a) and c) show the mean and other statistics over 2020-2060 for each index.*

2. Viability of agricultural sub-sectors is sensitive to the type of policy regime

Protectionist policies (higher trade barriers or higher subsidies) lead to slightly higher average profits (5.21 percentage points higher for subsidy, 7.28 for barriers, under no shocks), particularly for ruminant production (**Figure 2**). However, the real benefit for production sectors is that these policies reduce the number of years in which the sectors face negative profits. Higher subsidies and trade barriers are especially beneficial by this measure for the production of oilcrops, pulses, starchy roots, and wheat production.

With increased protectionist policies, domestic production is boosted and the self-sufficiency of food supply is greater than under the BAU scenario. However, the UK diet continues to be supplied mostly from imports. In the median runs, no more than 39% of demand is met from domestic production in 2060 across all scenarios. The subsidies and higher trade barriers improve self-sufficiency the most for monogastric products, wheat, and starchy roots. Interestingly, it is only under higher subsidies that the UK starts to produce meaningful amounts of either sugar or fruit and vegetables, relative to the demand for consumption.

Some sub-sectors in agricultural production are more sensitive to the type of policy regime than others. It is only under higher subsidies that sugar, fruit and vegetable production become sufficiently viable in the UK for domestic production to increase. The profit margins for ruminants are vastly improved, although still negative, when either higher trade barriers or subsidies are implemented. The improved certainty of positive profits benefits oilcrops, pulses, starchy roots, and wheat production considerably more than other sub-sectors. The protection through higher import barriers results in even higher frequency of good profits for these sub-sectors, even when global shocks occur.

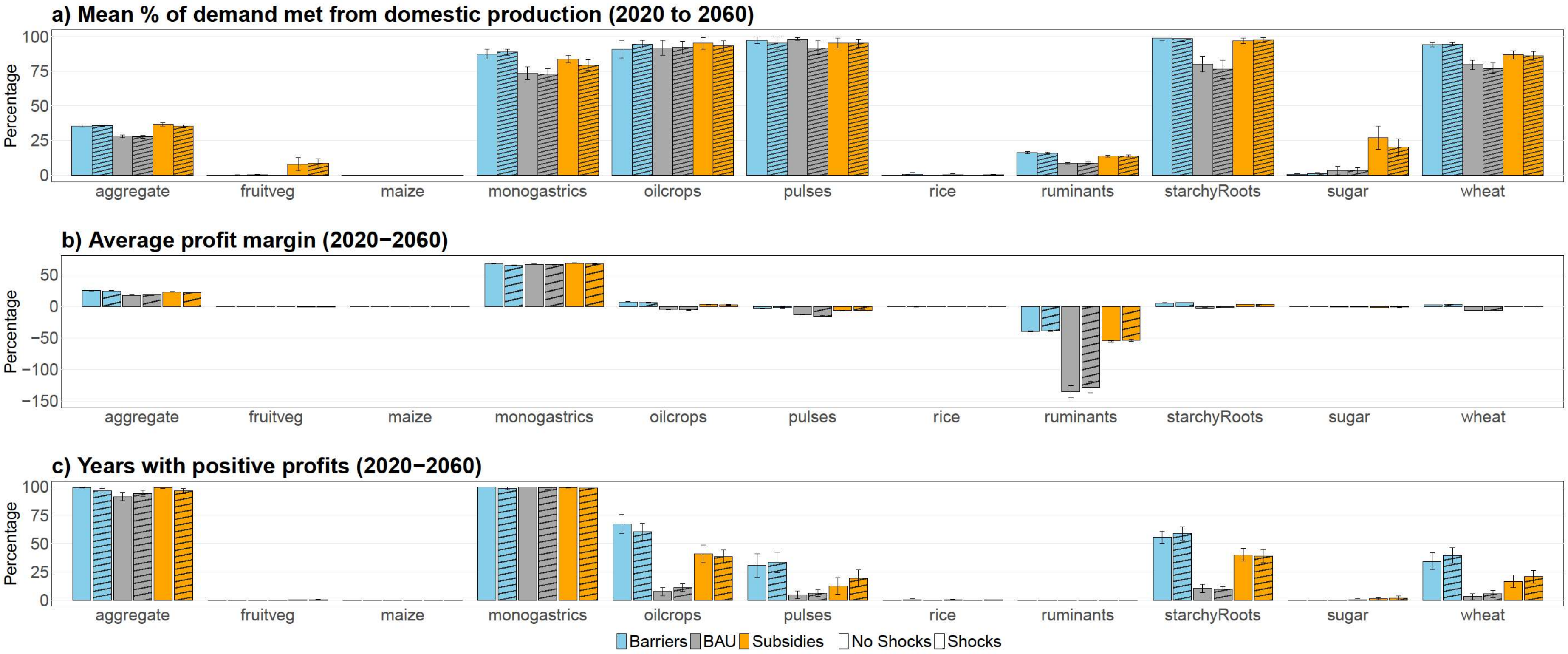
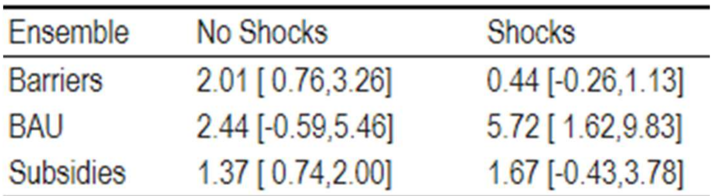


***Figure 2: Agricultural production sector indicators**. Average indicators for agricultural sector on aggregate and by subsector over 2020-2060. Self-sufficiency of UK food supply is shown by the mean percentage of domestic demand that is met from domestic production; average profit margin shows the net profit as a percentage of total revenue; and the final measure the percentage of years in which the sector or sub-sector achieved a profit margin greater than 5%. Error bars indicate 95% confidence intervals derived from 50 Monte Carlo simulations.*

Another consideration for the agricultural sector is its contribution to GDP, which we simulate in the model with a basic measure of value-added. **Table 1** shows that the average annual growth rate in agricultural value-added is highest under BAU. This is consistent with the relative fall in UK production as a percentage of food demand under the alternative policy scenarios. The protectionist policies improve viability for some sub-sectors, but overall growth in the sector is lower. Furthermore, under the BAU case, global shocks lead to an increase in the growth of value-added as global prices have risen in some years. In contrast, when shocks occur under higher trade barriers, GDP growth falls to close 0.44% on average annually. This likely reflects a continued reliance on imported feed for animal production.

Table 1: Average annual agricultural GDP growth over 2020-2060 (percentage). *Agriculture GDP is measured as the value-added: revenue less costs of production. Brackets show the 95% confidence interval from the 50 Monte Carlo simulations*



Ensemble	No Shocks	Shocks
Barriers	2.01 [0.76,3.26]	0.44 [-0.26,1.13]
BAU	2.44 [-0.59,5.46]	5.72 [1.62,9.83]
Subsidies	1.37 [0.74,2.00]	1.67 [-0.43,3.78]

3. *Higher trade barriers lead to increased environmental footprint of UK agricultural production*

We can capture resource use for agricultural production in terms of land use, water, fertilizer and other inputs. Whilst these only capture a limited range of the resource use associated with primary agriculture production (i.e. resource use for transportation and processing are excluded), they do provide an indication of the environmental impact of UK diets.

The implementation of the protectionist policies leads to important changes in the nature of agricultural production. There is a shift across all policy scenarios away from pasture and into cropland in the UK, although very minimal change in total agricultural land (less than 1% change in natural land area between 2020 to 2060 under all policy and shock scenarios, and not significantly different from zero at 95% significance level). However, this shift towards cropland is most pronounced under higher trade barriers, and least under subsidies (**Figure 3: Indicators for UK environmental impact of productionFigure 3**). The effect of global shocks is to further exacerbate this change in land use as producers respond to higher global prices for crops. The mix of animal feed between pasture and feed crop changes little, but pasture land becomes more efficient – furthering the intensification of agricultural production under protectionist policies. It is also important to note that this shift is land use is largely driven by the design of the policies in our simulations – the higher trade barriers benefit products which do not rely on feed inputs, and the subsidy policy is applied per unit of land cultivated for crops.

The application of nitrogen for agricultural production is a key measure for the potential environmental footprint of production. The nitrogen balance in the soil is an important proxy for greenhouse gas (GHG) emissions from agriculture and leaching of nitrogen pollution into waterways[16]. From **Figure 3**, we can see that the effect of protectionist policies is to increase the intensity of agricultural production in the UK to use more nitrogen and more irrigation. The effect is most stark for fertilizer use. Under higher trade barriers, total nitrogen applied to cropland annually increases by over 20%, compared to less than 10% under the BAU case. This increase is less under subsidies but still more than BAU.

Interestingly, this shift to more intensive agricultural production is not matched by an increase in the average crop yields. Crop yields under the BAU case increase slightly more than in the other policy regimes, despite considerably less fertilizer and water use. This is evidence that the protectionist policies are pushing production into less productive land, with potentially much greater impact on the local environment and GHG emissions.

It is also important to note that this shift in land use towards crop production coincides with a fall in the UK's production of animal products. As noted earlier, the UK diet changes very little and indeed continues to consume approximately 17% of daily calories from ruminant meat and dairy products. The GHG emission from livestock from UK agriculture would therefore fall with respect to animal products, but the environmental impact of this component of the UK diet has just been exported elsewhere in the world.

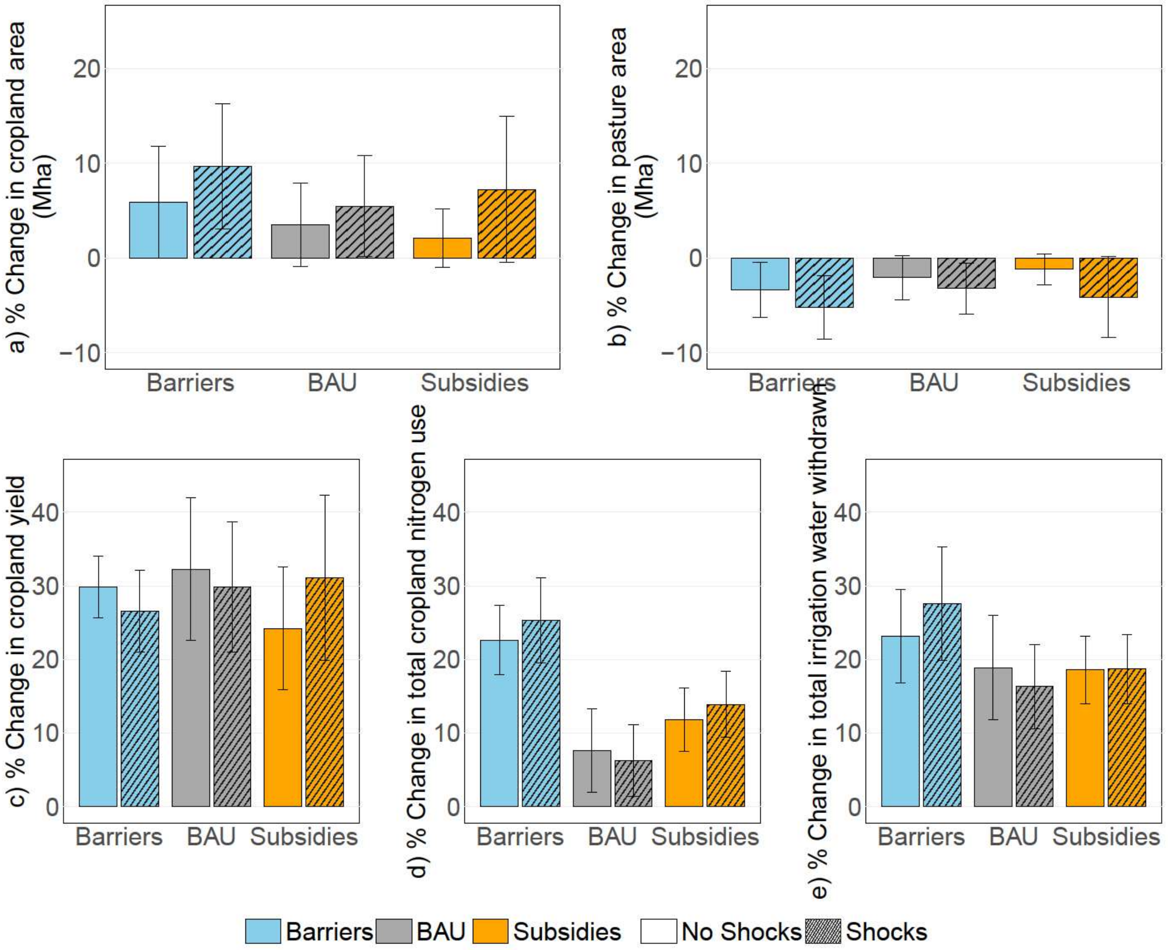


Figure 3: Indicators for UK environmental impact of production. *Change in land use allocation (a, b), output per ha on cropland (c), and input use (d,e) between 2020 and 2060 across all policy and shock scenarios. Again, error bars indicate 95% confidence intervals derived from 50 Monte Carlo simulations.*

IV. Discussion

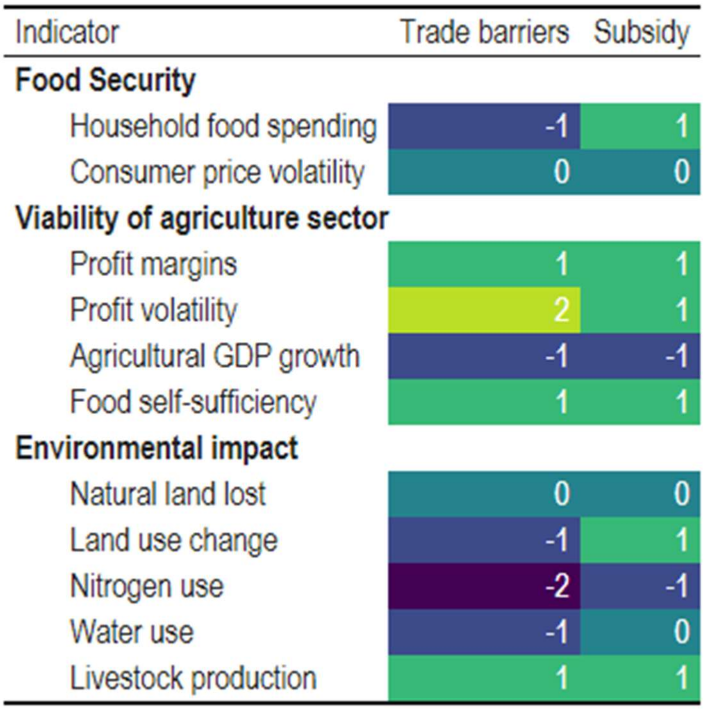
Given all these indicators, what can we say about managing the UK food system for resilience? **Table 2** provides a ranking of the policy regimes, relative to BAU. It serves to highlight the trade-offs policymakers may face in designing agricultural and food policy for multiple resilience objectives.

The higher level of producer support given to agricultural production, particularly through higher trade barriers, brings a trade-off between supporting the viability of the sector, at the expense of potential environmentally damaging changes in the production system (i.e. more intensive cropping).

Increasing a production-based subsidy for agricultural production seems to balance these trade-offs. Household food costs are kept lower than under the BAU, and the volatility of prices under shocks is similar to the alternatives. There is a greater cushion for the production sector but with less pressure on the environment compared with higher trade barriers.

The question which follows is how to design a subsidy that achieves increased capacity for domestic production, whilst adhering to any restrictions on agricultural subsidies under new trade agreements, incentivizing positive environmental impacts, and improving the affordability and availability of food for UK households. The subsidy we have simulated is a simplistic one with a 12% subsidy on the costs of production per hectare across all crops. A more nuanced and well-targeted subsidy policy has the potential to improve upon the environmental outcome of the simulations presented here.

Table 2: Effect of policy regimes for resilience*. Trade barrier and subsidy policies are ranked relative to the BAU policy scenario. If they lead to a better (worse) outcome than BAU for a particular resilience indicator, then they are ranked as 1 (-1). If both policies are better or worse than the BAU, they are then ranked relative to each other.*



Indicator	Trade barriers	Subsidy
Food Security		
Household food spending	-1	1
Consumer price volatility	0	0
Viability of agriculture sector		
Profit margins	1	1
Profit volatility	2	1
Agricultural GDP growth	-1	-1
Food self-sufficiency	1	1
Environmental impact		
Natural land lost	0	0
Land use change	-1	1
Nitrogen use	-2	-1
Water use	-1	0
Livestock production	1	1

Price level versus stability

The affordability of healthy diets in the UK is an increasing problem [17]. Over 2002-2012, the prices of all food increased, but the rate of increase was significantly greater for healthier foods than for less healthy foods [18]. Fruit and vegetables are the most expensive per kcal, compared to other food groups, which largely drives the difference in the affordability of healthy foods. Families earning less than £15,860 per annum would need to spend up to 42% of their disposable income to afford the recommended healthy diet [19]. The modelling results indicate that the type of policy emphasis at the macro-level for the agricultural sector has considerable implications for the affordability of food for consumers. Of the scenarios that were modelled, increasing subsidies in the UK leads to improvement in the affordability of food.

However, food security is broader than solely the average price level over the year. Volatility in consumer prices can lead to days or weeks in which households worry about being able to afford food, skipping meals, or reducing their meals due to lack of disposable income. This broader definition of food security has revealed rising numbers of vulnerable households in the UK which would be defined as severely food insecure [17]. Our simulation show that it is somewhat inevitable that volatility in global prices will pass through to food costs for UK consumer. Across all our simulated policy regimes the increased volatility in domestic prices under the BAU case was matched by the increased volatility under the more protectionist policy regimes. Market competition and power in the food value chain will influence the extent to which the increased volatility is absorbed by consumers or by other agents in the value chain, which is not accounted for here. However, the nature of the UK diet and its continued reliance in imported food means that price volatility from global markets will continue to be an issue, and one which affects lower income households disproportionately. Policymakers should pay attention both to the level of prices and their stability if they seek to strengthen food security for all UK households.

Consumer food security may be the primary objective of a food system, but the ongoing viability of the firms and producers in the food and agriculture sector are a crucial component of maintaining a reliable supply of food to consumers in response to severe shocks and over the long term. Our modelling framework provides indication of the overall pressure on the sector by considering the margin between the projected average production cost and the domestic consumer price. We do not specifically model the behaviours of food retailers, processors and other firms, but rather we consider the overall pressure on the entire sector. The distribution of power along the value chain determines which actors benefit or bear the cost of fluctuating profit margins. Competitive behaviour will determine whether a change in input prices is passed onto consumers, or absorbed into firms' margins [20]. Changes to land use and production occur more slowly than price changes, therefore profit margins will vary with price shocks as supply is slower to adjust. Profit margins therefore have an important effect on the resilience of the UK production sector.

Most UK agricultural production sectors are vulnerable to global production shocks. Furthermore, the size of their profit margin is strongly affected by the policy scenario. Sectors, such as monogastric livestock production, where there are consistently large and positive margins, will be best placed to maintain production when positive or negative prices or production shocks affect the sector. Domestic production of wheat, starchy roots and oilcrops, in particular, are only consistently profitable with the protection of higher subsidies or trade barriers. With such vulnerability in the UK's agricultural sectors, production shocks can easily lead to several years of non-positive profits, thereby eroding the capacity of a farm, business, or sector to absorb further shocks.

A striking trade-off that is demonstrated by the model simulations, is the potential damage to value-added or GDP from agriculture sector when protectionism is pursued in the policies. The annual average GDP growth is markedly higher under the business-as-usual case when shocks occur. The benefit of protectionism in improving the self-sufficiency of UK food supply is found. However, this benefit is limited in scope as our modelling shows that the UK will continue to rely on imports for key products for nutrition security such as fruit and vegetables, and ruminant meat and dairy products.

Environmental impact

Growing attention is being paid to the carbon or environmental footprint of diets, particularly for western countries with high meat consumption and high reliance on food imports [21]. The long-term sustainability of our planet and the ecosystems which support food production are critical for food system resilience. The average GHG emissions per kg from fertilizer, manure, and rice cultivation (excluding land-use change and transport emissions) in UK agricultural production is similar to that of imported EU food, but lower than that of total UK food imports [22]. The implication is that imported food increases the total GHG emissions arising from the UK diet. Given that both the protectionist policies we simulate imply over half of the UK diet will continue to be imported, emissions from imported food is crucial to consider.

Furthermore, these same policy regimes lead to potentially higher GHG emissions from UK agricultural production. Total nitrogen applied to cropland increases, particularly with higher trade barriers, without a commensurate improvement in crop yields. This implies that nitrogen efficiency (output per unit of nitrogen applied) declines under higher trade barriers. According to FAOStat, the UK is already in the top 15 countries for nitrogen use (global average is 69.7 kg/ha, EU is 90.4, and the UK is 169.8). Therefore, our simulations indicate that more protectionist agricultural policies have the potential to increase the UK agricultural emissions, if they do not incentivize low emission practices.

UK land use for agricultural production changes very little across policy scenarios but is much more sensitive to global production shocks. Spikes in global prices can lead to increased production, intensification and land use expansion in the UK. Hence, the net effect on the domestic versus global distribution of the environmental impact of the UK diet will depend upon the crop and the type of shock. Evidence suggests volatility in global prices has the potential to considerably change land use and the resource intensity of production in the UK.

V. Conclusion

The heavy reliance of the UK food system on imports leads to a stark trade-off between policies which may successfully safeguard lower prices for UK households, but which come with negative environmental consequences. Our analysis has demonstrated that a policy emphasis towards raising trade barriers may improve the viability of agricultural production sectors, but will lead to higher food costs for households and an increase in GHG emissions from agriculture. An emphasis on subsidies to UK agricultural production has greater potential to balance the benefits of lowering household food costs, supporting the viability of the production sector, with relatively lower environmental impact. Further study would be needed to consider a more nuanced system of subsidies, than has been simulated here, which could incentivize lower emissions whilst also achieving other food system resilience goals. The lesson here for policy makers is to maintain easy and low-cost access to global agricultural production whilst also supporting UK production sectors in order to increase resilience for UK household food security, and the economic viability of UK farm businesses.

The policies we have explored might improve resilience of the agricultural production sector – but they cannot deal comprehensively with the environmental or household food security aspects of resilience. The level of self-sufficiency can be changed via subsidies and increased trade barriers, but some dependency on imports will remain, leading to exposure to global shocks to the food system. Diets are also likely to continue to include livestock products and the consequent environmental impact (whether from UK or imported production), therefore measures to impact consumer preferences are required beyond the food supply measures considered here.

For policymakers seeking to redesign food and agriculture policy in light of Brexit, and in the face of unforeseen shocks such as the Covid-19 pandemic, the lessons from this analysis are that even relatively small policy-induced changes to costs and prices can have a considerable impact on the capacity of UK farm businesses to adapt to shocks. Furthermore, environmental sustainability of the

UK diet can be supported through a two-pronged approach of facilitating trade in those products which are more sustainably produced in the rest of the world, and simultaneously supporting domestic production in those which can be sustainability produced in UK agricultural conditions. Nuanced policy combinations of subsidy, regulation, and trade can achieve a more resilient and sustainable food system for UK producers, the environment and ultimately household food security.

Methods

Quantatitive global land-use model: LandSyMM

LandSyMM is a global land use, ecosystem and food-system model that clandombines spatially-explicit, biophysically-derived yield responses with socio-economic scenario data to project future demand, land use, and management inputs [10,11]. Within the LandSyMM framework, PLUMv2 is an agricultural trade and food demand model which is coupled with the LPJ-GUESS ecosystem functioning model [10,11,23,24] (see **Figure 4** in Supplementary Material). For each country and timestep, the agricultural land use and level of imports or exports are determined through a least-cost optimisation that meets the demand for food and bioenergy commodities in each country.

A key innovation of the model applied in this paper is a revised method to endogenously project food demand, which allows for price changes to directly influence country-level food demand. In other models, and the previous version of LandSyMM, food demand is purely a function of income per capita and total population. This price-sensitive food demand projection is key for effectively modelling the trade, land use, and food security implications of shocks to global food production. Demand for food commodities is calculated at each timestep at a country level for eight commodity groups: cereals, oil crops, pulses, starchy roots, sugar, fruit and vegetables, ruminant livestock products (both dairy and meat), and monogastric livestock products. Demand is calculated by the modified, implicit, directly additive demand system (MAIDADS, Preckel, Cranfield & Hertel (2010), Gouel and Guimbard 2018). The MAIDADS system uses income levels, food prices and empirically-estimated price and income elasticities to estimate subsistence and discretionary consumption levels and captures the nonlinearity of the relationship between food demand and income (more detail in supplementary material). Subsistence consumption levels within a country are constant and do not vary with price, whereas discretionary consumption levels respond to income and price. The demand system gives rise to a relationship between income and food products such that calories are consumed in the form of staple foods (cereals, oil crops and pulses) at low-income levels but this shifts to meat and fruit and vegetables as incomes rise. Conversely, as prices increase, consumption shifts away from 'luxury' goods such as meat and fruit and vegetables back towards staple crops. If a country cannot afford subsistence levels of consumption then, in effect, the average person in the country is malnourished, consuming too few calories. In this instance, demand for food products is calculated by scaling desired subsistence consumption by the ratio between income available for food expenditure and the desired subsistence consumption.

Increase in demand for commodities is met by in-country expansion or intensification of crop production or by imports from the global market. Commodities produced in excess of a country's domestic demand are exported to the global market. Countries in any given year are either net exporting or net importing for each commodity. The global market is not constrained to be in equilibrium, instead allowing over or under supply of commodities buffered through global stocks. Prices are updated for the next year based on the aggregate stock levels. For example, oversupply of a commodity on the global market decreases the price as stocks rise; this reduces the benefits from its export and reduces the cost of importing it, creating a tendency to correct for the oversupply. For each commodity a single tariff free price exists in each time step, which is adjusted for transport costs and other barriers, e.g. tariffs, to obtain country specific prices. LandSyMM determines land use solutions on a 0.5° grid to meet country level demand in a land use optimisation step. Within the land use optimisation, the model uses spatially specific crop yield responses to intensity inputs (i.e. nitrogen fertiliser and irrigation water), various land use costs (such as land conversion costs and input costs), protected area constraints and trade costs (see Alexander et al., 2018 for more details on the land use optimisation). The effective domestic price which is used to determine demand for the next time step, is a weighted average of the import price and the tariff free price according to the proportion of food supply that is imported versus domestically produced. Therefore, countries which import most of their food will face higher prices.

The model is designed to explore macro-level pressures on the UK food system, on an annual basis. UK land use decisions are dependent upon changes in the global market through trade and the assumption of the UK being a small open economy for which the global price influences the domestic price. Although we focus on food production, demand, and land use for the UK in the analysis, the same decisions for every country in the world are modelled simultaneously. In this way, built-in to the model are projected global population and income changes, according to the shared socio-economic pathways[*]. Socioeconomic parameters, population trajectories and GDP trajectories are in line with the "middle of the road" socio-economic pathway (SSP2), with trends largely exhibiting historic patterns [25,26]. The climate and atmospheric CO_2 forcing projections for RCP 6.0 was used as it is considered the Representative Concentration Pathway [27] most consistent with SSP2 [28].

Building the scenarios: Randomized production shocks

A distribution of shocks was derived from observed significant deviations in annual production from historical trends. We are careful to describe these as production shocks rather than weather or climate shocks as they are based on production data, rather than weather data. Production could be disrupted by weather, pests or diseases, conflict, or other social, economic, political, or climatic drivers. Following the methodology of Cottrell et al., we use historical data to derive a mean and distribution of production shock for each of the 8 LandSyMM crop types (wheat, rice, maize, fruit and vegetables, oil crops, pulses, sugar, starchy roots) [29]. We fitted local polynomial regression (LOESS) models with a span of 0.6 to aggregated annual production data for all countries and crops using the FAOSTAT production quantity 1961–2014 dataset (FAOSTAT). We regressed model residuals against lag-1 residuals; any outliers in this regression, data points with a Cook's distance of > 0.35, were included as a shock. We considered shock points associated with a loss in production relative to a previous 6-year median production baseline. The combination of parameters used for shock detection in the analysis were selected as those that minimised the sum of squared residuals with the median of this range through time (as in Cottrell). The parameters used here are similar to those used in the analysis by Cottrell et al., and Gephart et al.[29,30]

In any given year, we calculate the number of shocks occurring using a region-specific shock rate. To calculate this shock rate, we divide the total number of shocks detected over the historical time period in each region and for each crop sector by the number of years used for detection. We then divide the number of shocks detected for a given year in the region by the number of countries in the region to compensate for the different number of countries within each region. We use this shock rate to determine the number of shocks in a region for each crop type. We determine the magnitude of the shocks from the production shock distributions derived from the historical data. The shocks are randomly assigned to countries within the region.

The impact of the historical production shocks on global prices was found to be lower in the model than was observed in reality, particularly during the food price crisis of 2007-2008 (see validation in supplementary material). Therefore, calibration was done in order to replicate the magnitude of the observed price effects, which resulted in multiplication of the production shock by 10. It is this

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[*] SSP2 is used for all the simulations in this paper as it represents the business-as-usual case.

frequency and magnitude of shocks that is used to randomly generate a set of production shocks by year and by region over 2010-2060 (see Figures 7 & 8 in Supplementary Material).

In the simulation, the production of a particular region is determined by the least-cost food supply optimization per country per year. Then, any production shock is applied to reduce the production level by the magnitude based on historical patterns. The revised level of global production is used to adjust the global price that is used by the demand system to determine final consumption for that year. In this way, we simulate a production shock which occurs after producers have made their production decisions for the year and are unable to adjust in response to the shock until the subsequent year. The shock therefore affects the consumer price and level of food demand, but agricultural production is unable to adjust to the shock until the following year.

Building the scenarios: Policy regimes

The simulated policy regimes are (i) the BAU case (based on SSP2); (ii) a doubling of UK agricultural subsidies for crop production; and (iii) a doubling of UK trade import tariffs for all foods (Table 3). The BAU scenario is where policy parameters in LandSyMM have been selected to closely reflect those observed around 2010. For the subsidy scenario, we consider the effect of the UK government doubling its subsidies to crop production for food consumption (i.e. not animal feed, nor animal production). This is applied as a negative cost of production per hectare. For the trade barrier scenario, the UK import tariff rate is doubled for all products.

Table 3: Policy scenario parameters. *BAU levels for these parameters are derived from OECD's Producer Support Estimates (subsidy rate), and the Country MFN Weighted Average for 2000-2010 from the World Bank's World Integrated Trade Solution database (trade barrier). CIF price is the import price at the point of entry which is made up of the cost of the good plus insurance and freight costs.*

Policy regime	Subsidy Rate (% of unit cost per ha)	Trade Barrier (% of CIF price)
BAU (BAU)	6%	12%
Higher UK subsidy	12%	12%
Higher UK import tariffs	6%	23%

Measuring resilience

We report results for three aspects of the UK food system: (i) the food affordability and diet of UK consumers, (ii) the cost of production and profit margins for UK food sectors, and (iii) the environmental impact of UK diets. Resilience of a socio-ecological system (SES) cannot often be measured directly, but rather through proxy measures. A similar approach is used here in measuring food system resilience. Proxy measures are identified which are correlated with resilience of the system itself [31,32].

Table 4: Outcome measures to capture food system resilience

Aspect of food system	Quantitative variable from model	Measure of interest
Diet and its affordability for consumers	Societal cost of food supply Average spending per person per day on food	Level (index) & coefficient of variation
Cost of production & profit margins	Net margin by food sector (net profit/revenue)	Level
	% of UK food demand met by imports (self-sufficiency)	Level
	Frequency of years with >5% profit margin	Level
Environmental impact of diets	Agricultural land by area and type (pasture, cropland, natural)	Level and % change
	Nitrogen & irrigation use for UK food consumption	% change
	Livestock production	% change

For several outcome variables from our model (Table 4), the approach was to consider the deviation of trends from the non-shock simulations, as well as measures of the mean and variation of certain variables over the time period. The coefficient of variation provides a measure of variance as a percentage of the mean. The underlying assumption is that greater volatility in variables, such as prices, is negative for long term stability of the food system [33]. For other output variables, it makes more sense to consider the mean across policy scenarios, or relative to the non-shock simulation.

UK food security is measured through two measures. The societal cost of food supply is an index of prices, without subsidies taken into account, using the 2010 consumer diet as weights. The spending index uses consumer prices that include the effect of subsidies on reducing market prices, and weights these by the current average individual diet for each year. For the spending index, the dietary weight varies over time, unlike the societal cost of food.

To understand the pressures on the UK production sectors due to global shocks, we calculate the average profit margin by food type. This profit margin is rooted in the costs of production, which are determined by the optimization of land use at the core of the global land-use model. This optimization determines the decisions of land use and inputs for production, which is used to calculate the average unit cost of production. It is assumed that the UK economy is perfectly open to trade, therefore the upper bound on the UK domestic price is the import price.

We can calculate location-specific production costs by agricultural commodity, due to the geospatial detail of the model. This production cost represents the resource requirement for production of the commodity on a particular grid-cell. The model uses a global price for fertilizer and other input costs. Irrigation costs are spatially determined based on aridity measures. The cost of agricultural land expansion is related to the amount of managed and unmanaged forest in the gridcell. The only input cost which is affected by market forces is the cost of feed for animal production.

The environmental impact of the UK diet is calculated from the average production cost per ton as the basis for a resource index – a relative indicator of the amount of resources (water, fertilizer, land, and other inputs) required to produce the average UK diet. The proportion of the supply that is imported or produced domestically is used to weight the location-specific production cost for each food type. This weighted production cost is then used to calculate the total resource intensity of the average UK diet. These weightings change over time as the model responds to short- and long-term trends. Data on land use – natural, pasture, and cropland – by area are also reported.

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Supplementary Material

Additional figures and tables

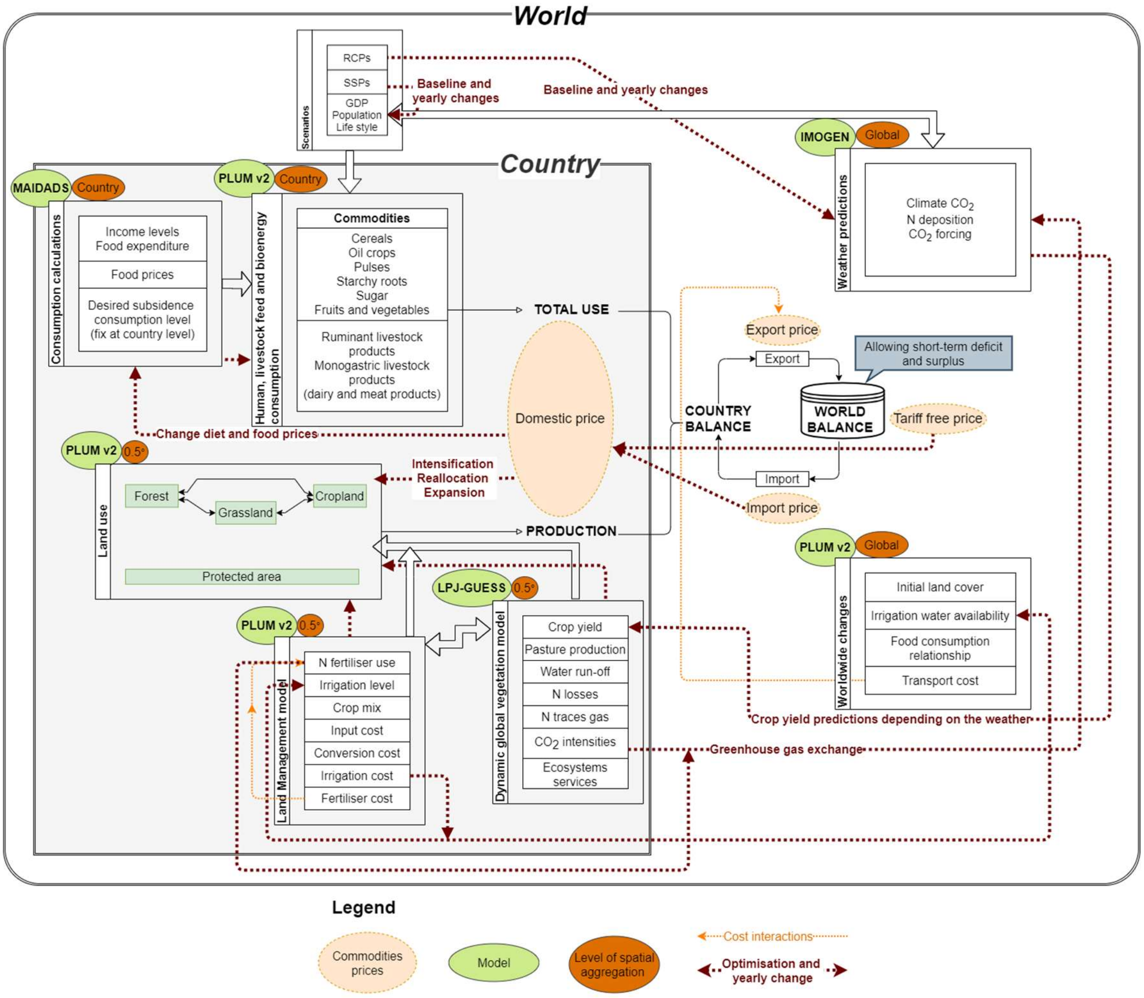

Figure 4: Diagram of LandSyMM model

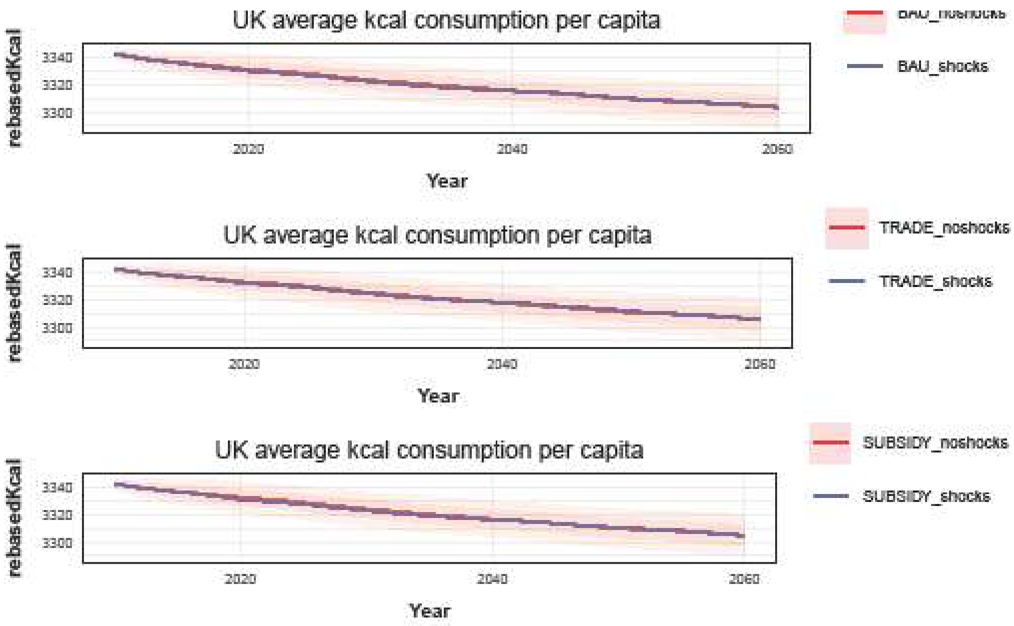

Figure 5: UK calorie consumption per capita. *Red shading indicates the 90% and 95% confidence interval for the policy scenarios without global production shocks. Figure is based on model simulation results.*

Validation

To better understand the relationship between production shocks and global prices in the LandSyMM model, the observed historical patterns of production shocks over the period 1990-2013 were simulated and the resulting price index is shown in Figure 6 (black lines). The plots show the observed price index over the same time period from the OECD-FAO Agricultural Outlook database for wheat and rice. These figures clearly show that either the model does not fully capture the pass-through of production shocks to global prices, or that the observed price volatility during that period was due to more than just production shocks. For example, it is well documented that weather-induced disruptions to wheat and rice production were only part of the story behind the food price crises of 2007-08 and 2011-13. Financial speculation, oil prices, and reactionary export bans have been shown to have exacerbated the impact of production shocks on prices [34,35].

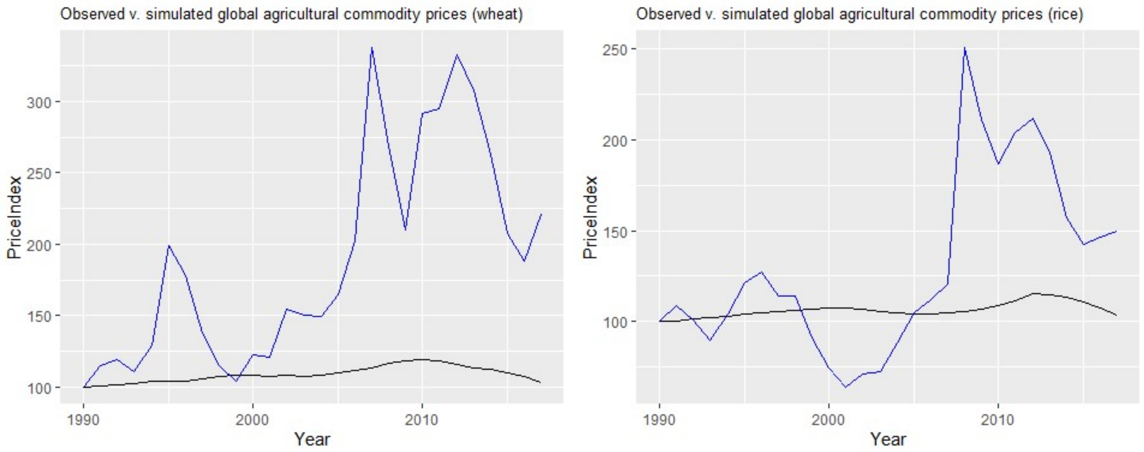

Figure 6: Observed and simulated agricultural commodity prices 1990-2018. *Blue line represents the OECD-FAO Agricultural Outlook Data for global commodity price indices. Black lines are price indices from the simulated model using historical disruptions to production.*

One definition of a resilient system is the amount of energy required to transition to an alternative state [9]. By this definition, our modelled food system is highly resilient. As shown in Figure 6, modelling the historical production shocks leads to very little disturbance to global prices compared to the empirically observed prices. This characteristic of the model should be kept in mind throughout the paper – i.e. that the modelled system in certain dimensions, is much more resilient than the empirically observed food system.

This characteristic is not unexpected. Intra-annual price variation in storable commodity markets is often greater than inter-annual variation [36,37]. The timing of knowledge and information about a production shock between planting and harvest will affect how much stocks are then used as a buffer. This is particularly true for the storable commodities included in our model (cereals, starchy roots, oilcrops, and pulses). Our model does not capture intra-annual variation in prices and, therefore it is expected that the simulated annual price variation would be less than the observed price variation which is reflecting both inter and intra annual price changes.

Randomized Production Shock Scenarios

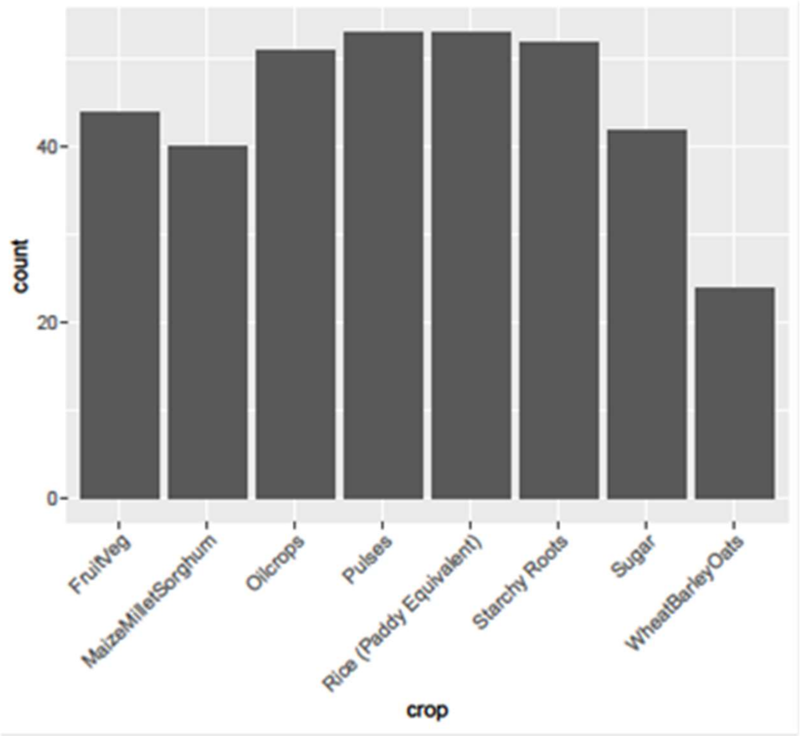

Figure 7: Distribution of global shocks*. Bars indicate the no. of years in which a production shock occurs for that crop. The model was run for 50 years. The average shock size was to reduce production by 40.21%, the maximum was 99% and the minimum was 00.00%. This chart represents the random draw of shocks which are used for the simulations which follow.*

The frequency of the shocks is relatively evenly spread across different agricultural commodities (Randomized Production Shock Scenarios

). Shocks occurred most frequently for pulses, rice, and starchy roots, and least for wheat and fruit and vegetables production. The production shocks are solely for non-animal products. Animal production is affected indirectly through higher costs for animal feed (maize, wheat, oilcrops, pulses). Figure 8 shows the magnitude of the shocks in terms of the reduction in production applied. The average shock factor is 0.40, i.e. production is reduced by 40%.

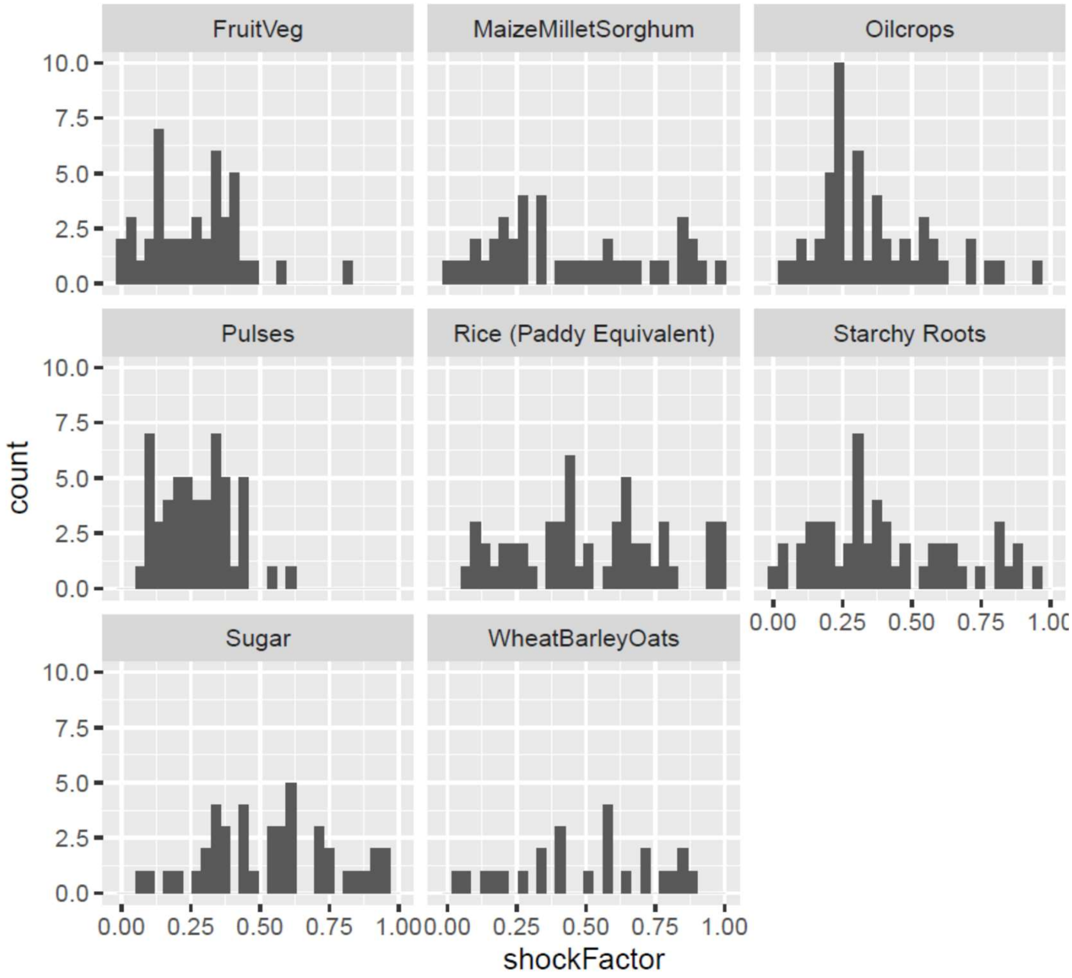

Figure 8: Distribution of shock magnitudes. *shockFactor is the percentage reduction in production for a shock to a particular region in a particular year. The average shock factor is 40%, i.e total production for that region in that year is reduced by 40%.*

Food demand system of LandSyMM

As with many of the integrated assessment models, the future projections for food demand have previously been based on a simple log-linear relationship between country's GDP per capita and per capita demand for each of the eight food commodities modelled by PLUMv2. This is approach to modelling and projecting food demand is detailed in a previous paper (see Alexander et al., 2018). This current paper is the first to make use of a more developed food demand component of PLUMv2, which has been based upon the work of Gouel & Guimbard (2018) and Preckel, Cranfield, & Hertel (2010).

The aim was to improve the demand component so that country food demand would respond to both prices and income level. The challenge with this is that many of the standard demand systems used for similar land use models assume constant income elasticities, ignore price elasticities, or are not good at estimating demand across the whole range of country income levels that are observed in the world. The Modified, Implicit, Directly Additive Demand System (MAIDADS) meets several of the criteria required for PLUMv2. It was developed by Preckel, Cranfield & Hertel (2010), and extended to focus on food demand by Gouel and Guimbard 2018. The latter have provided the data and estimation code which they used freely and publicly, and is the basis for adapting their model for PLUMv2 purposes. The primary difference from Gouel & Guimbard (2018) is the aggregation of foods into eight groups. We keep the same number of groups (the demand system can only handle up to 10 separate commodities), but have adjusted them to match with those of the production module. The data used for the initial estimation of the parameters of the demand system were prepared using the same methods as Gouel & Guimbard, i.e. 2010 FAOStat food balance sheets and trade values to infer prices for each food group.

To summarize, the MAIDADS demand system is estimated using maximum likelihood estimation methods from observed country-level consumption and income data for 2010. For each time step of PLUMv2, these parameters are used to estimate the expected food demand for each country based on the prices from the previous time step and projected GDP per capita according to SSP/IASA. The expected food demand is then used to determine the level of production and imports. The demand component is then used again after prices are adjusted to account for the production decision and any yield shocks.

The estimated parameters for the model are in the table below and can be compared to those of Gouel & Guimbard (2018). These parameters mean that the income and price elasticities vary across country and across time as GDP per capita changes. In addition, food demand per country is rebased to 2010 observed levels to incorporate the variation in diets across countries that is not explained by GDP per capita. The demand component estimated a level of subsistence and discretionary demand. Subsistence is based on GDP per capita and not influenced by prices. Discretionary demand is influenced by both GDP per capita and prices. Confidence intervals have been calculated using bootstrapping. α and β are the parameters which determine discretionary spending. It is only discretionary spending which is allowed to be responsive to prices in the demand system, therefore it is important that at least some of these parameters are nonzero, in order for demand to be responsive to prices when projecting demand endogenously using PLUMv2. δ and τ are the parameters which determine subsistence consumption.

Table 5: Demand system parameters. *These are the parameters used for the LandSyMM. Demand saturation is assumed therefore β is set to zero for all food products. Value of the Log-likelihood function from the econometric estimation is provided, to give a sense of the joint significance of the estimated parameters.*

	α	β	δ	τ
Cereals	0.006 (0.00,0.02)	0.000	0.661 (0.60,0.68)	0.452 (0.40,0.46)
Roots	0.042 (0.01,0.09)	0.000	0.075 (0.05,0.12)	0.028 (0.02,0.07)
Oilcrops and Pulses	0.002 (0.00,0.01)	0.000	0.144 (0.12,0.16)	0.246 (0.23,0.26)
Sugar	0.040 (0.03,0.05)	0.000	0.045 (0.03,0.06)	0.184 (0.17,0.19)
Fruit and Veg	0.440 (0.35,0.56)	0.000	0.026 (0.01,0.04)	0.094 (0.09,0.11)
Ruminants	0.196 (0.14,0.27)	0.000	0.012 (0.00,0.05)	0.236 (0.23,0.25)
Monogastrics	0.178 (0.10,0.23)	0.000	0 (0.00,0.02)	0.165 (0.16,0.18)
Non-food	0.0976 (0.00,0.23)	1.000	2.36 (0.00,5.76)	286.334 (260.77,307.70)

ω	1.171 (1.02,1.40)
κ	-0.756 (-1.18,-0.20)
Log-likelihood function	902.91

Limitations of LandSyMM-PLUMv2 food demand component

The demand elasticities built into the food demand component of the model capture the response of households to price spikes. They will either forgo other food items or non-food spending to keep consuming the product, or temporarily stop consumption. However, the model only considered broad food groups or commodities and therefore cannot capture the shift in household demand between products within a food group e.g. from cheese to milk, or cheese and ruminant meat. Furthermore, it does not capture the adjustments households make in the quality or types of products they purchase. For example, if the price of wheat increases, the shift of households from buying artisanal sourdough to processed white bread is not captured. For this reason, the price elasticities in our models are relatively low. It is likely that there is even more adjustment within food groups than between them when price and income shocks occur. Given that the primary concern is food security, the focus on broad food groups is sufficient, however.

The demand system that is used to estimate the UK diet is based on projecting the number of kilocalories consumed per day. Other literature has estimated price and income elasticities for UK food demand in terms of expenditure, rather than calories consumed. This is a fundamental difference between the demand model used in this paper and other papers [39,40] which is a demand system in terms of expenditure rather than calories consumed. Given that our attention is on food security in terms of the diet actually consumed we see this as an improvement over other modelling approaches. However, this contributes to the small elasticities which are derived, since the amount that people consume changes little in response to prices. We would expect there to be adjustment in the spending per calorie in response to prices, which is not captured in our demand system.

Summary of the Business-as-usual model simulation

Whilst the main focus of the paper is to compare food resilience measures across policy regimes, it is instructive to understand the underlying trends in the business-as-usual case which result from LandSyMM. **Figure 9**, below, provides a summary of key measures for household food security, the agricultural sector, and the environmental footprint.

Household food security under BAU

The societal cost of food declines steadily over the period 2020-2060. This is due to improving technology and efficiency, which is an assumption of LandSyMM. The impact of shocks is to increase the cost of food for a few years initially, but over the full time period, the higher prices stimulate higher production globally and therefore a fall in food costs. When we account for diets changing in response to prices, the spending on diets by households actually increases slightly over the time period, by 3.5% in the median run. The occurance of shocks causes a higher increase, 5% to 2060, but also includes several years where spending is considerably higher (5% higher than *no shocks* at the peak). The difference in these measures reflects small shifts in the composition of the diet in response to prices. By 2060, there is a 3% increase in calories from sugar, 7% fall in calories from starchy roots, 1.4% fall in cereals, 2% fall in ruminants. Overall, the simulated shocks cause an increase in volatility of food costs by 1.5%.

Agricultural Sector under BAU

Domestic production remains fairly stable over the period 2020-2060, as a proportion of food demand. UK average diet changes very little over the time period either in total number of calories nor the distribution across commodities. When shocks occur, production of monogastrics products and wheat seem to be most affected by the global price volatility. Producers of monogastrics are reliant upon imported and domestic animal feed from crop products – when the price of these products are volatile, it translates into lower profits for monogastric production. As shown in **Figure 2** of the main article, LandSyMM indicates that most agricultural sectors in the UK struggle to make consistently positive profits under BAU. The exception is monogastric production, which has a high average profit margin and achieves positive profits in most years. At the other extreme is ruminant production that under BAU faces average loss margin of 135% of revenue. Production continues despite this shortfall as the model is based on finding the cheapest way to meet demand, from domestic production or imports, rather than maximizing producer profit.

Environmental impact under BAU

As reported in the main text, the total UK agricultural land area is projected to change little under the BAU simulations. There is a slight change in the composition of agricultural land to increase cropland and decrease pasture area. Global production shocks exacerbate this effect. The reason for these trends are (i) the assumed increase in productivity in agriculture leads to a small shift towards crop production, and (ii) the implemented production shocks affect crops only, therefore price increases for crops incentive increased production of crops in the UK. The rates of nitrogen and irrigation use are largely stable over the time period simulated. Crop yields increase by about 30% over 2020-2060. This increase is slightly less when shocks occur. We can infer that when the prices for crops are elevated due to global markets, the inflated price motivate expansion of production through increase in land area, rather than solely productivity improvements or increased intensity of production.

Overall, the business-as-usual scenario represents a stable UK food system, whereby the characteristics of food demand and agricultural production change very little. The main driver of changes that are observed are either a steady technology-drive productivity increase, or the occurrence of global production shocks that change incentives for UK producers.

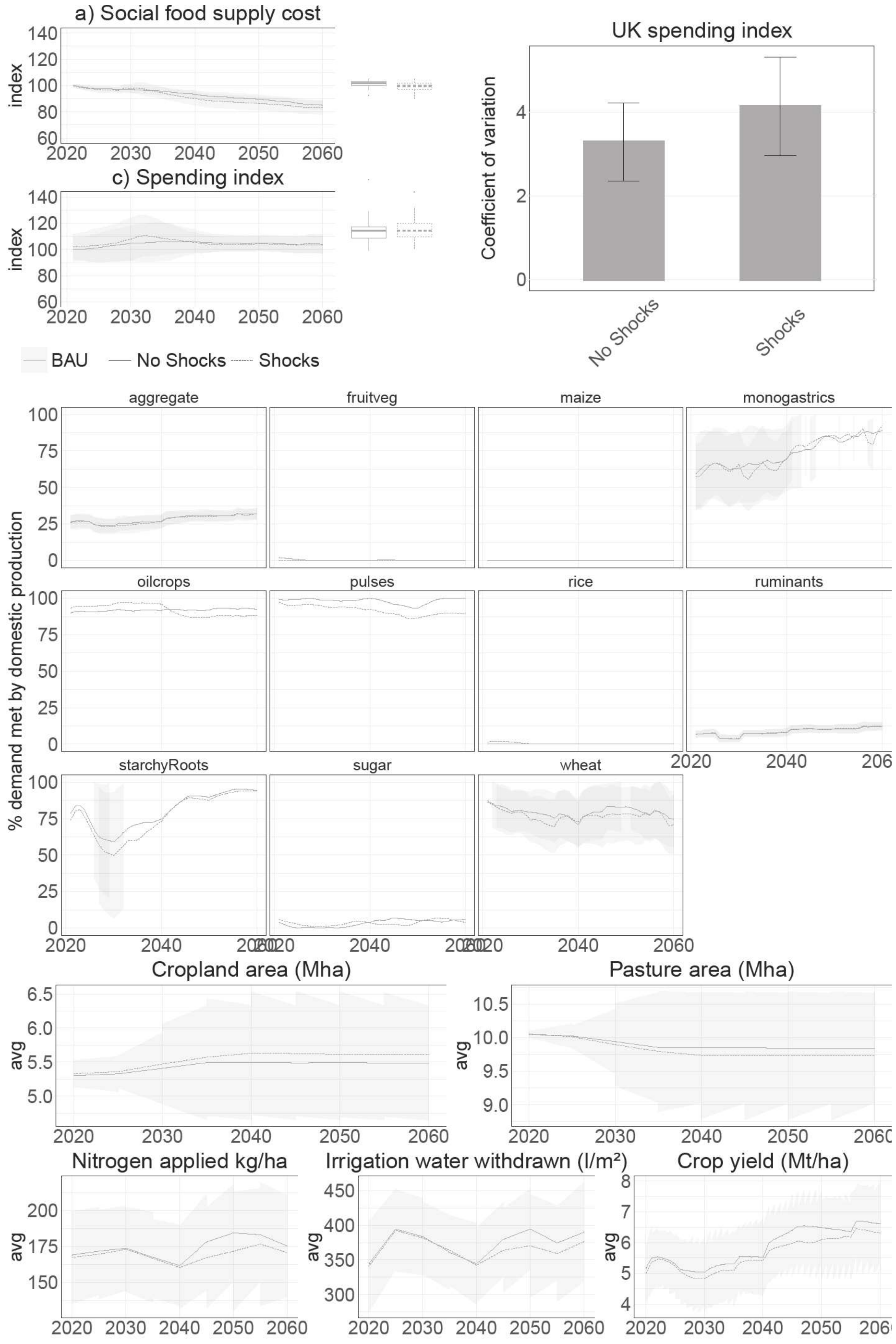

Figure 9: Key measures for the business-as-usual scenario. *Dotted lines indicate simulations when shocks occurred; solid lines are when no shocks occurred. Shaded areas are the width of 2 standard deviations.*

Further background to the UK food system

UK Food Security and Global shocks

Global commodity markets had periods of high and volatile prices during 2007-08 and 2011. Much of these effects were keenly felt in less developed countries which are also highly reliant on food imports, where rising food prices were linked to social unrest [34,41]. Was the same impact felt in the UK food system? Davidson et al. look particularly at the relationship between global commodity prices and UK domestic retail prices[20]. They find that global price volatility and the cumulative effect of global price inflation, oil prices, and exchange rates has a greater impact on UK retail food prices than domestic demand pressures and food chain costs. However, food spending as a proportion of household incomes is low in the UK[2], particularly compared to less developed countries. Therefore, the average household in the UK is better placed to absorb rising food costs without reducing the quantity or quality of their diet. Over the period of food price inflation, the average calorific intake of UK households, and the composition of their diets changed little in the aggregate.

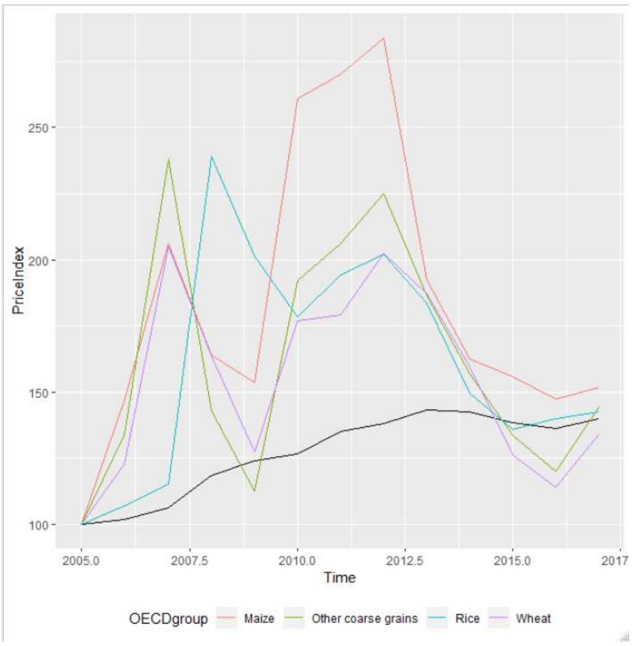

Figure 10: UK consumer and global price volatility (2005-2017). *Black line is the UK Consumer Price Index and Coloured lines are the global commodity price indices from OECD-FAO Agricultural Outlook dataset.*

However, several studies have shown that good quality diets are unaffordable for low-income households in the UK. The diet which meets the government recommended Eatwell Guide, would cost up to 30% of the disposable income for the lowest income decile households, compared to 12% for the top income deciles [19]. Healthy foods have been found to be more expensive than unhealthy foods in the UK, with the difference in price increasing over time [18].

Until recently, household food security has not been regularly measured in the UK. Estimates of consumption and spending on food, with detail on nutrient intake, has been captured by regular nationally representative surveys, but these have failed to capture the uncertainty some households face over weekly disposable income which can lead to skipped meals and has been linked to food

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[2] Average UK household spent 11% of gross income on food in 2018. For the lowest income decile, it is 14%. (Table A5, Family Spending Tables, Office for National Statistics).

bank use. Households facing unemployment, disability, and low incomes are associated with severe food insecurity in the UK, with vulnerability to food insecurity worsening among low-income and benefit-reliant households since 2004[17,42]. Therefore, future price volatility will hit those with fixed low incomes all the more[43].

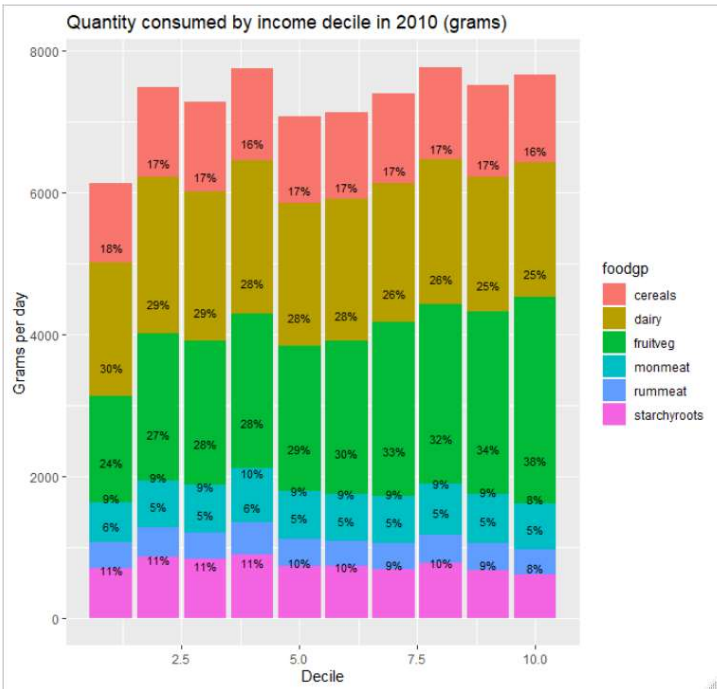

Figure 11: UK household diets by income decile (2010). *Source: DEFRA Family Food tables, derived from the Living Costs and Food Surveys.*

UK Food Supply

According to a recent DEFRA report, 34% of UK farms failed to make a profit in 2017[1]. Over 90% of farm business income came from direct subsidies for grazing livestock and mixed farms, with 60-70% from subsidies for cereal and crop farms. In particular, small businesses and family farms are more vulnerable to the consequences of shocks than large commercial operations, which may have access to broader markets. Further pressure on UK agricultural production comes from rising energy costs due to energy policies to reduce UK emissions. Dairy and cereal farmers have seen falls in income in recent years; specialist poultry has seen an increase [44]. Furthermore, there has been a shift in demand away from mutton and beef since the 1980s, which is only likely to continue given the increasing consumer attention to the high environmental impact of meat consumption [45]. The RSA Fork in the Road report (2019) concluded that the economics of farming are becoming more challenging[46]. Recruiting labour for agricultural production is difficult with lack of housing and public services in rural areas. Furthermore, farming is now only a small part of rural life, with most farmers diversifying away from food production.

As part of the EU, the UK enjoyed zero-tariff imports from the rest of the EU. Any imports from outside the EU would face the same import tariffs. For 2010, the MFN weighted average import tariff for EU countries was 11.07% for food products.[3] This measure is an applied tariff weighted by trade

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[3] Data from World Integrated Trade Solution database using UNCTAD MFN Weighted Average indicator. The average of Most Favoured Nation tariffs weighted by their corresponding trade value. https://wits.worldbank.org/Default.aspx?lang=en accessed October 2018.

values. The same measure for the rest of the world varied from less than 5% for Australia and Hong Kong, to over 50% in countries such as New Zealand, India, and Egypt. The EU tariff rate is similar for food products as that of China and Canada, and slightly higher than the United States. Of course, the UK's import tariffs are highly uncertain going forward, both in terms of the de jure tariffs and in terms of the composition of countries from which the UK imports its food. Both of these factors have the potential to change considerably as the UK leaves the European Union and established new trading relationships. In the initial post-Brexit phase, tarrif and quota free trade with the EU has been maintained for food and agriculture, but there has been increase in non-tarriff barriers. The effect on the average import tariff for UK food supply will depend upon the diversity of sources for particular products, which may change under the new trading regime.

Similar to import tariffs, the UK agricultural production sector has received subsidies and other forms of support through the EU's Common Agricultural Policy and associated mechanisms. Generally, about 55% of support that agricultural producers receive is linked to agricultural production (about 20% of gross farm receipts). The rest of the support is conditional on environmental compliance [47]. The focus of support in recent years has been on dairy and livestock producers, as well as fruit and vegetable producers. The distortions to prices which are created by such support are greatest for poultry, beef and veal products. Overall, the producer support to agriculture in the EU has declined from 2.5% of GDP in the 1980s to approximately 0.6% in 2015-17 [47]. The same indicator for the United States was 0.2% of GDP, and 0.85% for Japan. Again, the amount and structure of support to agriculture and rural development in the future for the UK will become a new realm of political debate post-Brexit, with plenty of uncertainty.

Environmental sustainability

In addition to the impacts of shocks to the food system for UK households and agricultural production, the UK's import dependence means that the environmental impact of the UK's food consumption is realized abroad, as most of the land use and greenhouse gas emissions are located beyond the UK's borders [22,48].

For UK production, projected climate change effects indicate there will be improved growing conditions due to warmer temperatures and elevated CO_2 levels. Potential shifts in production from the south and east, which is water-stressed, to the north and west of England, with the potential to also increase disease and pest vulnerability[49].