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Projecting the effect of crop yield increases, dietary change and different price scenarios on land use under two different state security regimes

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ABSTRACT

Using an Agent-Based Model with a two-scale decision making process incorporating economic, geographic, social and political subsystems, we projected the rate and proportion of land use change in England and Wales from the year 2000 to the year 2050. These projections were used to assess the impact of proposals to improve arable yields, change diet and reduce consumer waste under two contrasting political ideologies, protectionist or free trade, on the proportions and rate of change of agricultural land use. The model does not calculate what is possible to achieve but what is probable, given the simulated processes, which are based on landowner satisficing behaviour and government political ideologies. Our main finding is that protectionist policies produced the least change. We also found that arable crop yield improvements, dietary change and waste reduction promoted pasture over arable use because these drivers reduced arable income on marginal arable land. The proportion of land in private and farm-forestry, a land use proposed as a greenhouse gas (GHG) mitigation measure, reduced, when private and farm-forestry was not a protected use and when there were no incentives to plant or maintain trees.

KEYWORDS
Agent-based model; land use change; England and Wales

1. Introduction

It has been estimated that around 6% of UK land is urban (Rae, 2017). Around 71% of the UK land is under farmed agriculture (Defra, 2019). Forests account for 13% of the total land area of the UK, with land cover amounting to 10% of land area in England, 15% in Wales, 19% in Scotland and 8% in Northern Ireland (Forest Research, 2019). In contrast, on a global scale, for countries across the world, the average proportion of land under agriculture is just over 37%. In European Union (EU) countries, the average proportion of land under agriculture is around 42%. For countries around the world the average forest cover is just over 30%, while for EU countries this average is higher at just over 38% (World Bank, 2019). The UK has considerably more land under agriculture and less forest cover than either the world or EU averages.

The land use structure that currently exists in the UK is a result of thousands of years of competing requirements; the advancement of new and abandonment of old technologies (Ang et al., 2010), growing populations, empire (Cain, 1980), agricultural lobbying (Monbiot, 2014) and food security (Defra, 2010). Despite the large proportion of land in agriculture, the UK is not food self-sufficient. The UK must rely on both home-grown and imported food products to be food secure (de Ruiter et al., 2016; de Ruiter et al., 2017). Even if the diet of the UK population

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were to be restricted to food items that could be grown in the country, the UK would still not be entirely self-sufficient due to an insufficiency of land of the required quality and crop yields (including grass) which rely on imported energy and fertilizer (Defra, 2008).

In the UK, agricultural land is classified by grades, which indicate productivity. Land grades 1–3a are usually deemed suitable for most types of arable farming. In England, the land grades 1–3 sub-grade (a) inclusively account for around 42% of farmland (Natural England, 2012) which means that around 30% of all English land is suitable for arable farming. Comparable figures for Scotland and Wales are, respectively, 8% (James Hutton Institute, 2017) and 7% (Welsh Government, 2019). The remainder of agricultural land is more suited to pasture, rough grazing, forestry and wild land. In the year 2000, the average UK wheat crop yield stood at around 8 t ha^{-1} (UKGov, 2011). In contrast, livestock yields can be expected to range from 1 t ha^{-1} for pork or poultry meat, to 0.3-0.5 tonnes ha^{-1} for beef or sheep meat (Kleanthous, 2009). Globally, it takes 100 times more land to produce a gram of protein from beef or sheep farming than from cereal farming (Clark & Tilman, 2017). The domestic production of home-grown beef and sheep has a significant effect on the environment (Garnett, 2007) and greenhouse gas (GHG) emissions.

There is further potential to increase crop yields. In the UK, it has been estimated that 47% of wheat yield improvement has been brought about by plant breeding (Silvey, 1994). Future yield improvements are expected to come about through improved plant solar energy capture and utilization and by increasing the proportion of the plant that is harvestable (Jaggard et al., 2010). Yields are thus expected to continue to improve in England and Wales (Spink et al., 2009). Sylvester-Bradley et al. (2005) concluded that in theory, UK wheat yields could reach around 19 t ha^{-1}. Current yield levels vary from 7 to 8 t ha^{-1} (Defra, 2005). However, constraints on development, research and physical practicalities mean that these theoretical limits are unlikely to be reached. More realistically, Defra (2005) estimated that average UK farm wheat yields could grow to be around 11 t ha^{-1} by the year 2025 and around 13 t ha^{-1} by the year 2050.

In the UK, debates around food security have moved away from domestic agricultural self-sufficiency. Defra's strategy unit concluded that a 'UK policy objective should be to secure fair prices, choice, access to food and food security through open and competitive markets' (Defra, 2008; Defra, 2014). Defra asserts that self-sufficiency would not insulate the UK from disruptions in the domestic supply chain or retail distribution system. Self-sufficiency would also open the UK to risks of adverse weather events, crop failure and animal disease outbreaks. In addition, the UK 'would continue to depend on imported fertilisers, machinery and certain foods for a balanced diet' (Defra, 2008).

In 2017, around 50% of food consumed in the UK was grown in the UK, the reminder was imported. The 50% imported comprises around 30% from the EU with another 2% coming from the rest of Europe. A further 16% of imports came from Africa, Asia, North and South America and 1% from Australasia (Defra, 2018). The three largest imported commodities by value (at 2017 prices) were fruit and vegetables, meat and beverages (Defra, 2018). The UK also exports food and drink, with a value of around £10.68bn in 2018 (Food and Drink Federation, 2019).

Both the world's and the UK's populations have been growing (ONS, 2017; UN, 2017). Feeding larger populations is an issue and may increase the risk of food insecurity and damage to the environment. Several solutions are proposed which include: (a) Sustainable Intensification; increasing arable crop yields but with fewer inputs (Godfray & Garnett, 2014; Smith, 2013), (b) Changing diets (Green et al., 2015) and (c) Reducing food waste (Gunasekera, 2015; Quested et al., 2011).

In a report 'Quantifying the impact of future land use scenarios to 2050 and beyond' Thomson et al. (2018) examine how mitigation measures could reduce GHG emissions from UK agriculture by 2050, while still maintaining current levels of per capita food production. The report identifies that agriculture and land use sectors need to make considerable progress on GHG emissions reduction, if the UK is to meet its future statutory emissions reduction targets. The models used in the report assume different levels of uptake of various technologies and behaviours. Several emission mitigation measures were considered, among them land-sparing strategies which included arable crop yield improvements, dietary change and consumer waste reduction. The report states that although 'the UK's land area is finite', 'increasing yields per hectare' can free up land for other GHG mitigation measures. The report found that scenarios with dietary change and arable crop yield improvement spared the most land for alternative uses such as forestry which according to Law et al. (2018) have strong GHG mitigation potential.

Crop yield improvements are a supply side strategy. By increasing arable crop yields future demand can be met from the same area of land, or, if improvements are sufficient, from less land (Smith, 2013; Strassburg et al., 2014). Dietary changes and reduced consumer waste are both demand side-strategies. Consuming less meat and dairy and reducing consumer food waste causes demand to fall for both livestock and crops, this is expected to either free land from agriculture or limit agricultural expansion (Smith, 2013; Westhoek et al., 2014).

After the 2016 EU referendum, the UK government stated that its intention was to leave the EU (Parliament UK, 2017). Given a possible UK move away from the protectionist agricultural policies of the EU toward a free trade approach, what are the implications for agricultural land use, land use change and for agricultural GHG emissions. As the UK is an importer of food, how will future world price trends affect land use? World food price trends have been predicted but show considerable variation depending on the source used. For example, Kruse (2018) suggests that wheat prices and other cereal prices are expected to remain relatively flat through to 2050, assuming improvements in yields show a linear trend. Alternatively the International Food Policy Research Institute (IFPRI) predicts that world grain prices will increase 30–50 percent over the period 2005–2050 (Msangi & Rosegrant, 2012), while meat prices in the same period will increase an additional 20–30 percent beyond the price levels seen in 2007/2008 (von Braun et al., 2008).

With 'data' available only for England and Wales, a land use projection was made of these two countries. The aim of the projection was to ascertain the likely composition and rate of change of agricultural land use under a variety of possible scenarios such as those given by Thomson et al. (2018). These are: changes to arable yield, food import price rises, dietary change and consumer waste reduction. Thomson suggests that it is possible that more agricultural land will be freed for GHG mitigation measures such as forestry. The question arises: Under any of these scenarios, given current farmer decision-making processes, will more agricultural land be freed for GHG mitigation measures such as forestry and, in addition, which political ideology (protectionist or free trade) spares most land and which produces most change?

The emergence of an agricultural landscape is the result of the interaction of many component parts. An example of which is the interaction of food prices, yield change, diet change, waste reduction, soils, climate, landowner behaviours and protectionist or free trade ideology. Together these interactions form a complex land use system. Modelling complex land use systems has been identified as an area for research (Briassoulis, 2008; Rindfuss et al., 2008). The modelling of an agricultural landscape system is particularly suitable for Agent-Based Modelling (ABM) (Marvuglia et al., 2018) as it allows decision making by agents at both local and national scales.

2. Method

Using an Agent-Based Model, the Biophysical, Land Use, Economic and Security model (The BLUES model; Reilly et al., 2020), we tested the effects of food security considerations, as expressed through either a protectionist or free trade ideology, arable yield increases, import price rises, dietary change and waste reduction, on land use and land use change. The BLUES model consists of representations of three interacting constraints and influences. These are (a) biophysical limitations, as determined by soil and climate; (b) social and economic interactions; and (c) security considerations. The model contains two types of agent – satisficing landowners (Bendor et al., 2009; Simon, 1955; Simon, 1956) and a government with a protectionist or free-trade ideology. A protectionist government is food security sensitive, applies export restrictions, forces land use change at times of crises, and uses subsidies. The reverse is true of a free-trade government, which relies on market forces to solve food security issues. Food security is determined by the formalization of a realist security theory based on Thucydides's *tri-fecta* of interest, prestige and fear (Gilady, 2018; Gilpin, 1981; Hammond, 2009; Rosen, 2005; Thayer, 2004; Wood, 2013).

The BLUES model was configured for two simulation experiments which ran the projections at a 1-km resolution. The first experiment looked at supply side change (yield improvement). The second experiment was concerned with demand-side change (dietary change and waste reduction). Both experiments explored their respective scenarios in the context of various global price change scenarios; and assumed, given the UK's economic position of being currently the fifth largest economy by Gross Domestic Product (GDP) and ninth, based on Purchasing Power Parity (Knoema, 2019), that the UK would be able to maintain imports of food to make up for deficits in its own domestic food production. The objective of the experiments was to discover which, if any, scenarios significantly influenced the proportion or the rate of change of land use and to make inferences about how this might impact GHG mitigation measures such as afforestation.

2.1 Data inputs and data sets

The model ran using inputs that generated the scenarios described in section 2.4. These inputs were indexes of food import prices, arable yield increases and different dietary demands or reductions in waste. The following input data were used:

a. Index of food import prices for the years 2000–2015 and three sets of projected import food prices for years 2016–2050. For these data projections, estimates of future food price trends were used (Kurse, 2018; Msangi & Rosegrant, 2012; von Braun et al., 2008).
b. Average UK wheat yields from the year 2000 to the year 2010 with three sets of projected yields from 2011 to the year 2050. For these data projections, estimates of future yield trends were used (Defra, 2005; Spink et al., 2009; Sylvester-Bradley et al., 2005).
c. We made three dietary and waste projections. One projection represented a diet in which meat consumption was reduced, another where consumer waste was reduced and a third where meat consumption and consumer waste were both reduced. The model simulates diet and waste reduction by adjustments to demand. If less is being eaten or wasted, demand falls.

The dietary parameters were calculated using the raw calorific value of wheat (The Good Taste Guardian BV, 2018) as a surrogate for crops, while beef was used as a surrogate for livestock products. Table 1 shows how the model diets were split between crop and livestock products. The parameter values for each of the three dietary projections are shown in the '*consumption in t*' column of Table 1 is split based on estimates of dietary changes.

2.2. Data output

Two output measures were selected, which were the proportions of each land use (by area) at the end of the projected period and the number of times land use changed. Together with the initial land use proportions, the proportions of each land use at the end of the period can be used to quantify the modelled change in the agricultural landscape. Inferences can be made using the estimated amounts of change as to the environmental impact of these changes. How often landowners changed land use provides an assessment of the landscape's stability, which may favour one use over another. Frequent and strong price swings are more favourable to the more flexible land uses and therefore favour agriculture over forestry.

2.3. Statistical analyses

The experiments were factorial by design, each experiment consisted of 18 scenarios, making 36 scenarios in total. The objective of the experiments was to discover which, if any, of the following factors influenced the proportion and rate of change of land use in the model: changes to crop yield, import price, diet, waste reduction and political ideology. To test the statistical significance of the factors on model output, an Analysis of Variance (ANOVA) was carried out. Stochastic elements within the model meant no simulation would be entirely the same; to account for variation each scenario was simulated 100 times. The results of the 100 replicates were averaged prior to ANOVA.

2.4. Scenario

All the scenarios started in the simulated year 2000 and were completed in the simulated year 2050. Each scenario started with identical land use distributions. The initial proportion of arable land was 32%, pasture 41%, private and farm-forestry 9% with no land abandoned. On initialization, each grid square was assigned a land use from a reference map of English and Welsh agricultural land uses as existed in the year 2000. This ensured that the initial land use for each grid square remained constant in all scenarios. The model was updated by new input values at each iteration (section 1.2.1). Each scenario was given an ID. Tables 2 and 3 detail each scenario by number.

3. Results

This section details the results from the two experiments.

Table 1. Dietary scenarios for dietary and waste reduction experiments in the BLUES model. The table gives the weight of crop and livestock product in tonnes (t) and kilograms (kg) and energy in kilocalories (kcal).

Baseline reference diet						
	kcal per capita		Consumer demand			
Type of demand	kcal / 100g	kcal / kg	kcal / day	total kcal / year	consumption in kg / year	consumption in t / year
Crop	329	3290	2,613	954,100	290	0.29
Livestock	115	1150	1,071	391,000	340	0.34
Scenario D1: Diet with reduced kcals, less consumer waste						
Type of demand	kcal per capita		Consumer demand			
	kcal / 100g	kcal / kg	kcal / day	total kcal / year	consumption in kg / year	consumption in t / year
Crop	329	3290	1,773	647,250	197	0.20
Livestock	115	1150	727	265,250	231	0.23
Scenario D2: Diet with less meat & dairy consumption						
Type of demand	kcal per capita		Consumer demand			
	kcal / 100g	kcal / kg	kcal / day	total kcal / year	consumption in kg / year	consumption in t / year
Crop	329	3290	3,317	1,210,523	368	0.37
Livestock	115	1150	369	134,503	117	0.12
Scenario D3: Diet with less meat & dairy consumption, reduced kcal, less consumer waste						
Type of demand	kcal per capita		Consumer demand			
	kcal / 100g	kcal / kg	kcal / day	total kcal / year	consumption in kg / year	consumption in t / year
Crop	329	3290	2,250	821,250	250	0.25
Livestock	115	1150	250	91,250	79	0.08

Table 2. The Experiment 1 scenario combinations used for projections of crop, price and government policy comparisons.

Free trade government		
ID	Crop yield improvement	World price change
S1	Crop yield no increase	Stable pricing no increase
S2	Crop yield no increase	Crop increase by 30% livestock 20%
S3	Crop yield no increase	Crop increase by 50% livestock 30%
S4	Crop yield medium increase	Stable pricing no increase
S5	Crop yield medium increase	Crop increase by 30% livestock 20%
S6	Crop yield medium increase	Crop increase by 50% livestock 30%
S7	Crop yield high increase	Stable pricing no increase
S8	Crop yield high increase	Crop increase by 30% livestock 20%
S9	Crop yield high increase	Crop increase by 50% livestock 30%
Protectionist government		
S10	Crop yield no increase	Stable pricing no increase
S11	Crop yield no increase	Crop increase by 30% livestock 20%
S12	Crop yield no increase	Crop increase by 50% livestock 30%
S13	Crop yield medium increase	Stable pricing no increase
S14	Crop yield medium increase	Crop increase by 30% livestock 20%
S15	Crop yield medium increase	Crop increase by 50% livestock 30%
S16	Crop yield high increase	Stable pricing no increase
S17	Crop yield high increase	Crop increase by 30% livestock 20%
S18	Crop yield high increase	Crop increase by 50% livestock 30%

3.1. Scenarios projecting variations in arable yields, import prices under protectionist and free-trade regimes

The results of Experiment 1 show that changes to crop yield and government market protections both had a significant effect on both the proportions of land use and the number of times land use changed. Changes to import prices only had a significant effect on the proportion of forest and abandoned land and the number of times land use was changed. In most cases the proportion of arable land is less in the year 2050 than for the year 2000. Only in two cases is there a greater proportion of arable land and this occurred under the highest rate of yield improvement. The proportion of land under forest always lessened, while the area under pasture and land abandonment always increased. All these effects were greater under a free trade policy than under a protectionist policy (see Table 4) (Figure 1).

Increasing yields did not lead to the expected fall in the proportion of arable land, although in general, there was less arable land in the year 2050 than in the year. The 'no yield improvement' scenarios

Table 3. The Experiment 2 scenario combinations used for projections of diet, price and government policy comparisons.

Free trade government		
ID	World price change	Diet type
S19	Stable pricing no increase	Reduced diet less consumer waste
S20	Stable pricing no increase	Low meat & dairy consumption
S21	Stable pricing no increase	Low meat, dairy crop and waste
S22	Crop increase by 30% livestock 20%	Reduced diet less consumer waste
S23	Crop increase by 30% livestock 20%	Low meat & dairy consumption
S24	Crop increase by 30% livestock 20%	Low meat, dairy crop and waste
S25	Crop increase by 50% livestock 30%	Reduced diet less consumer waste
S26	Crop increase by 50% livestock 30%	Low meat & dairy consumption
S27	Crop increase by 50% livestock 30%	Low meat, dairy crop and waste
Protectionist government		
S28	Stable pricing no increase	Reduced diet less consumer waste
S29	Stable pricing no increase	Low meat & dairy consumption
S30	Stable pricing no increase	Low meat, dairy crop and waste
S31	Crop increase by 30% livestock 20%	Reduced diet less consumer waste
S32	Crop increase by 30% livestock 20%	Low meat & dairy consumption
S33	Crop increase by 30% livestock 20%	Low meat, dairy crop and waste
S34	Crop increase by 50% livestock 30%	Reduced diet less consumer waste
S35	Crop increase by 50% livestock 30%	Low meat & dairy consumption
S36	Crop increase by 50% livestock 30%	Low meat, dairy crop and waste

led to the greatest fall in arable land use. Forest did not expand onto pasture land, but pasture expanded into private and farm-forest land. This was because private and farm-forest land in the model is not protected. While current UK law does not normally allow farming on forest land, it can occur. Agroforest schemes may introduce cattle or sheep, while deforestation resulting from the spread of tree pests and diseases and from forest fire, can provide an opportunity to extend grazing. The methods of calculating land

Table 4. The mean proportion of key agricultural land uses in 2050 under the different Experiment 1 scenarios at a 1-km resolution and mean change from the year 2000. Values in red denote a fall in the proportion and in green a rise. No increase in crop yield (CY=0), Moderate increase in crop yield (CY = M), high increase in crop yield (CY = H), no import price rises (*P*=0), moderate import price rises (*P* = M) and high import price rises (*P* = H).

1-km resolution model percentage of land use occupied at the end of year 2050 average of 100 simulations								
Land type	Arable %		Pasture %		Private & Farm-forestry %		Land abandoned %	
Initial (2000)	**31.92**		**40.59**		**9.01**		**0**	
Free trade government								
Scenario	2050	Change	2050	Change	2050	Change	2050	Change
CY=0 *P*=0	28.59	**−3.33**	49.25	**8.66**	2.29	**−6.72**	1.40	**1.40**
CY=0 *P* = M	28.85	**−3.07**	49.00	**8.41**	2.25	**−6.76**	1.41	**1.41**
CY=0 *P* = H	28.87	**−3.05**	48.99	**8.40**	2.26	**−6.75**	1.40	**1.40**
CY = M *P*=0	29.74	**−2.18**	48.09	**7.50**	2.25	**−6.76**	1.44	**1.44**
CY = M *P* = M	29.94	**−1.98**	47.92	**7.33**	2.21	**−6.80**	1.45	**1.45**
CY = M *P* = H	29.95	**−1.97**	47.91	**7.32**	2.21	**−6.80**	1.45	**1.45**
CY = H *P*=0	30.50	**−1.42**	47.36	**6.77**	2.22	**−6.79**	1.45	**1.45**
CY = H *P* = M	30.55	**−1.37**	47.33	**6.74**	2.20	**−6.81**	1.45	**1.45**
CY = H *P* = H	30.54	**−1.38**	47.32	**6.73**	2.20	**−6.81**	1.46	**1.46**
Protectionist government								
CY=0 *P*=0	29.89	**−2.03**	48.32	**7.73**	2.04	**−6.97**	1.28	**1.28**
CY=0 *P* = M	30.11	**−1.81**	48.10	**7.51**	2.03	**−6.98**	1.28	**1.28**
CY=0 *P* = H	30.12	**−1.80**	48.10	**7.51**	2.02	**−6.99**	1.28	**1.28**
CY = M *P*=0	31.44	**−0.48**	46.79	**6.20**	2.01	**−7.00**	1.29	**1.29**
CY = M *P* = M	31.63	**−0.29**	46.61	**6.02**	1.99	**−7.02**	1.29	**1.29**
CY = M *P* = H	31.62	**−0.30**	46.60	**6.01**	2.00	**−7.01**	1.30	**1.30**
CY = H *P*=0	32.43	**0.51**	45.86	**5.27**	1.98	**−7.03**	1.25	**1.25**
CY = H *P* = M	32.49	**0.57**	45.81	**5.22**	1.98	**−7.03**	1.24	**1.24**
CY = H *P* = H	32.49	**0.57**	45.79	**5.20**	1.99	**−7.02**	1.25	**1.25**

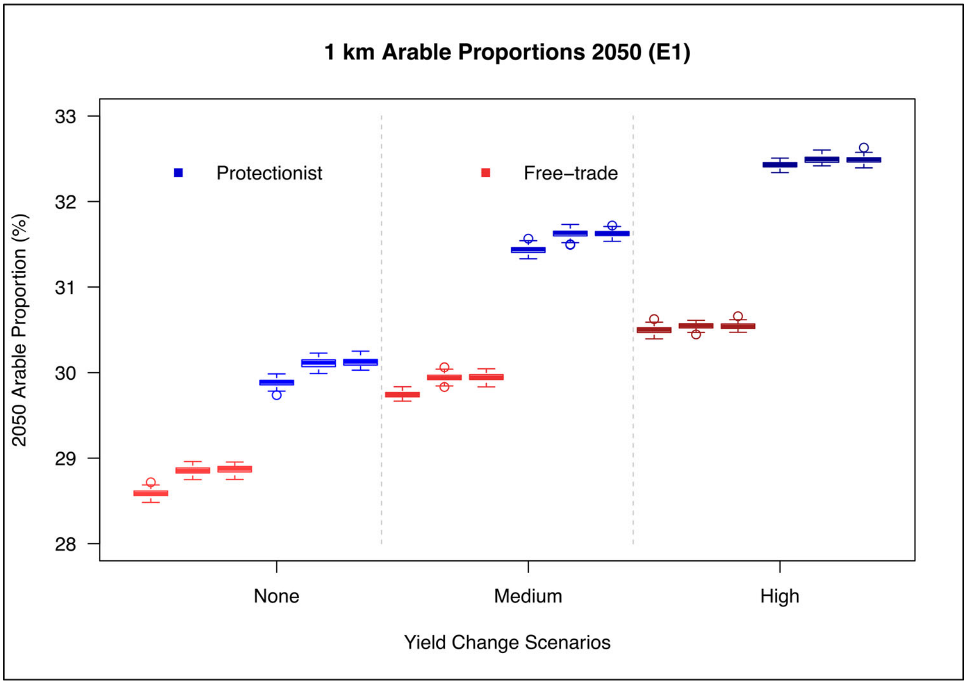

Figure 1. Projected change in arable proportions in the year 2050, under no, moderate and high crop yield change scenarios. Scenarios ID S1 to S9 (coloured red-brown) represent a free trade government, while scenarios ID S10 to S18 (coloured blue shades) represent a protectionist government. The three bands per grouping represent different scenario: S1-3 are paired with 10-12, and 4–6 with 13–15 etc.

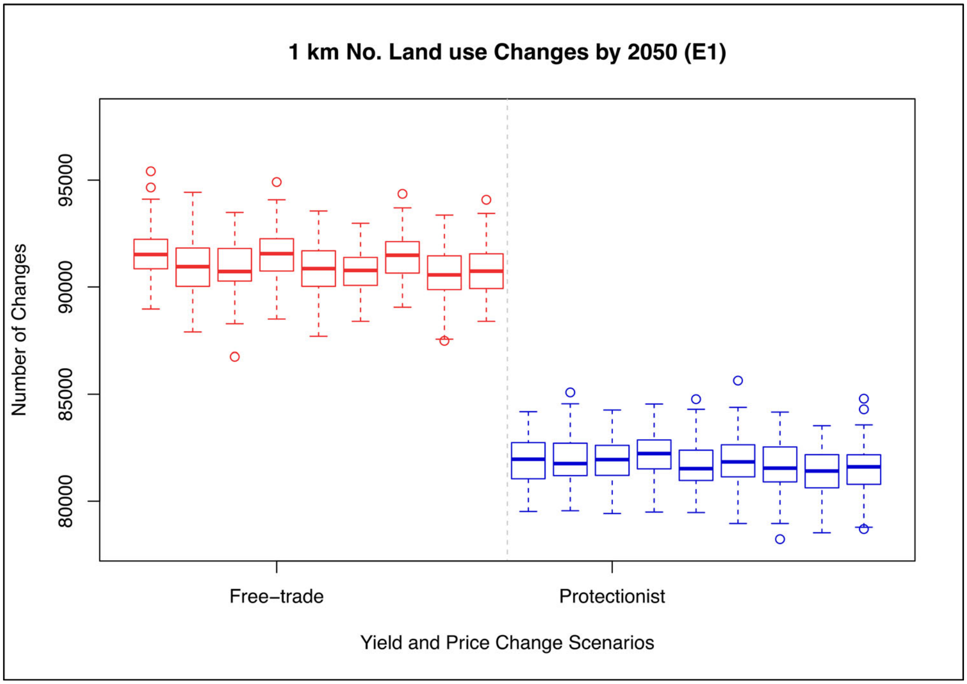

Figure 2. The effect of different experiment 1 scenarios on the mean total number of land use changes made by 2050. Scenarios with ID S1 to S9 (coloured red/brown) represent a free trade government, while scenarios with ID S10 to S18 (coloured blue) represent a protectionist government. The results show that modelled government trade ideology had an impact on the rate of land use change.

Table 5. The mean proportion of key agricultural land uses in 2050 under the different experiment 2 scenarios, at a 1-km resolution and the mean change from the year 2000. Values in red denote a fall in the proportion and in green a rise. No import price rises (*P*=0), moderate import price rises (*P* = M), high import price rises (*P* = H), Reduced diet less consumer waste (W), Low meat & dairy consumption (LMD) and Reduced diet less consumer waste (LMD&W).

1-km resolution model percentage of land use occupied at the end of year 2050								
average of 100 simulations								
Land type	Arable %		Pasture %		Private & Farm-forestry %		Land abandoned %	
Initial (2000)	**31.92**		**40.59**		**9.01**		**0**	
Free trade government								
Scenario	2050	Change	2050	Change	2050	Change	2050	Change
P=0 W	26.98	**−4.94**	50.71	**10.12**	2.41	**−6.60**	1.42	**1.42**
P=0 LMD	30.03	**−1.89**	47.73	**7.14**	2.33	**−6.68**	1.43	**1.43**
P=0 LMD&W	28.59	**−3.33**	49.07	**8.48**	2.57	**−6.44**	1.30	**1.30**
P = M W	27.19	**−4.73**	50.53	**9.94**	2.37	**−6.64**	1.42	**1.42**
P = M LMD	30.26	**−1.66**	47.52	**6.93**	2.31	**−6.70**	1.43	**1.43**
P = M LMD&W	28.68	**−3.24**	48.92	**8.33**	2.53	**−6.48**	1.40	**1.40**
P = H W	27.20	**−4.72**	50.52	**9.93**	2.38	**−6.63**	1.42	**1.42**
P = H LMD	30.27	**−1.65**	47.52	**6.93**	2.3	**−6.71**	1.43	**1.43**
P = H LMD&W	28.68	**−3.24**	48.92	**8.33**	2.52	**−6.49**	1.40	**1.40**
Protectionist government								
P=0 W	28.29	**−3.63**	49.85	**9.26**	2.11	**−6.90**	1.28	**1.28**
P=0 LMD	31.36	**−0.56**	46.75	**6.16**	2.11	**−6.90**	1.29	**1.29**
P=0 LMD&W	29.86	**−2.06**	48.21	**7.62**	2.25	**−6.76**	1.20	**1.20**
P = M W	28.51	**−3.41**	49.63	**9.04**	2.11	**−6.90**	1.28	**1.28**
P = M LMD	31.52	**−0.40**	46.59	**6.00**	2.12	**−6.89**	1.29	**1.29**
P = M LMD&W	30.01	**−1.91**	48.04	**7.45**	2.23	**−6.78**	1.24	**1.24**
P = H W	28.52	**−3.40**	49.64	**9.05**	2.09	**−6.92**	1.27	**1.27**
P = H LMD	31.52	**−0.40**	46.62	**6.03**	2.1	**−6.91**	1.28	**1.28**
P = H LMD&W	30.02	**−1.90**	48.03	**7.44**	2.23	**−6.78**	1.24	**1.24**

use options places forestry at a disadvantage. Free trade increased the number of times land use changed because no subsidies were available to cushion income falls; consequently, the agricultural landscape became more dynamic as landowners switched use more often (see Figure 2).

3.2. Scenarios projecting different diets and food waste regimes, import prices under protectionist and free-trade regimes

The results of experiment 2 show that both changes to diet, waste reduction and combined dietary change and waste reduction along with government market protections had a significant effect on both the proportions of land use and the number of times land use changed. Changes to import prices only had a significant effect on the proportion of arable and pasture land (see Table 5). In all cases the proportion of arable land is less in the year 2050 than for the year 2000. The proportion of land under forest always lessened, while the area under pasture and land abandonment always increased. All these effects were greater under a free trade policy than under a protectionist policy (see Figure 3).

Meat and dairy are the products of pasture grazing. In all of the simulations demand for meat and dairy fell which was expected to lead to fall in the proportion of pasture land, but this did not occur. Imports of crops and a decrease in demand for crops, by consumer waste saving in two of the three scenarios led to a fall in arable land and a conversion of arable land to pasture. Scenarios where no crop improvements were made, coupled by the fall in demand for arable crop tends to shift land use toward pasture. It is notable that in the scenarios where crop demand increases, the loss is loss of arable land is substantially lower.

4. Discussion

The results show that when crop yield is improved over time, for the highest yield increases, the proportion of arable land expands, but only under a protectionist government, (see Table 4 and Figure 4). With a moderate improvement in crop yield or when there is no improvement in crop yield, the proportion of arable land falls. Agricultural land, and in particular pasture, expands at the expense of private and farm-forestry and sometimes at the expense of

Figure 3. The effect of different scenarios on the mean number of land use changes made by 2050. Experiment 2 scenarios ID S19 to S27 (coloured red/brown) represent a free trade government, while scenarios ID S28 to S36 (coloured blue) represent a protectionist government.

arable land. Small areas of marginal land are always abandoned. The change in land use proportions and number of times land use changes are greater under free trade than protectionist policies (Figure 5).

In a study, with the UK as an example and by using both supply and demand side strategies Lamb et al. (2016) contend that it is possible to significantly reduce the UK's agricultural GHG emissions by removing land from agriculture. According to Lamb et al. (2016) agricultural technologies and dietary change could free up land (land-sparing) for other uses such as forestry which have strong GHG mitigation potential. According to Lamb et al. (2016) arable improvements coupled with dietary change (the consumption of less meat), and reduced food waste have the greatest potential for land-sparing.

The BLUES model results also generally agree with this. Both the Thomson et al. (2018) and Lamb et al. (2016) findings were based on theoretical models that extend from technical solutions. The implementation of these solutions is a matter of political economy (Lockwood, 2013). The addition of behavioural assumptions in the ABM will help us understand how these technical solutions will play out in a world with heterogeneous and differently motivated agents (Mercure et al., 2016). The application of free trade versus protectionist policies, although simplistically represented in the BLUES model, has shown that it is possible to account for food security responses that governments might make by incorporating their political ideologies. In a world where natural resources become scarce because of climate change, these political ideologies are likely to become more important, particularly where they effect trade, sovereignty, land ownership (Allouche, 2011; Scoones et al., 2019).

It has been posited that crop yield improvement would cause a fall in the proportion of land under arable production (Balmford et al., 2005). With higher yields, less arable land is required to meet demand. A decrease in the area under arable cropping, would, if it freed land for forest use, have environment benefits (Balmford et al., 2018). The BLUES model shows that, when per hectare arable crop yield is modelled to increase, between the years 2000–2050, the proportion of land under arable production in England and Wales does fall slightly (by up 3.3% of the land area of England and Wales) but for the highest projected yield increases, the arable area expanded. In fact, over the simulated 30-year period, the greatest fall in arable land use

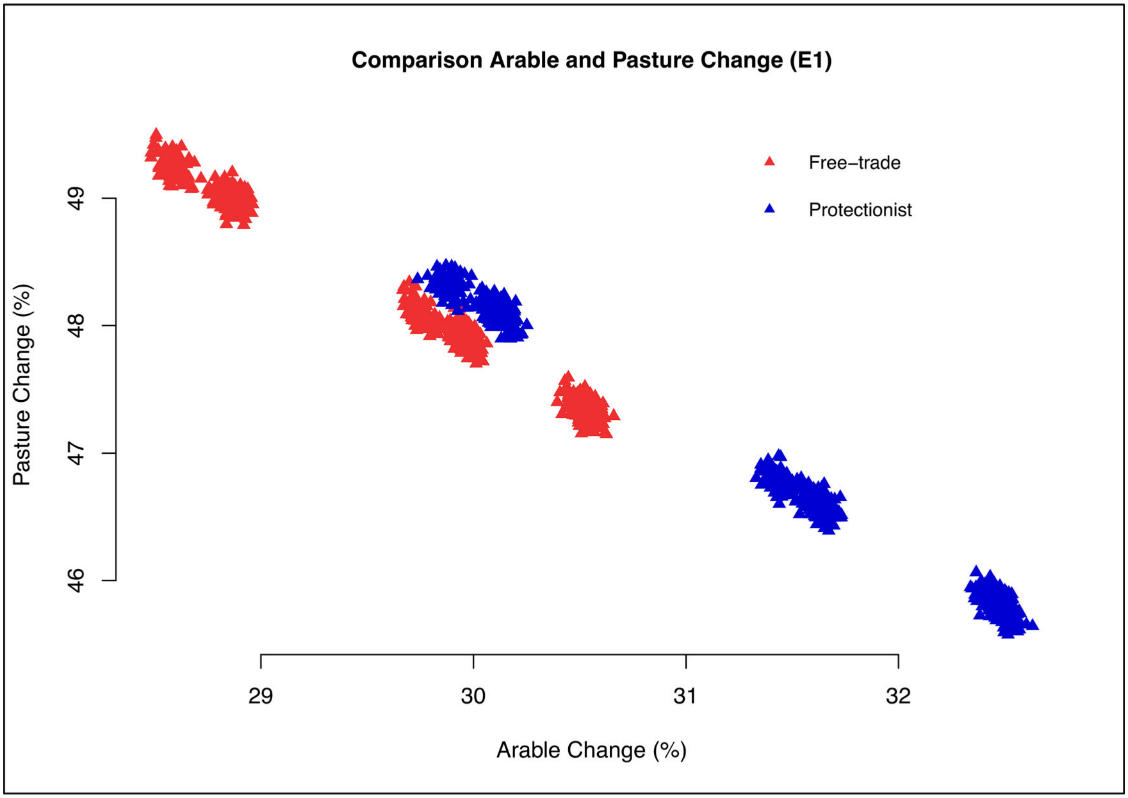

Figure 4. A comparison of land use change arable plotted against pasture under both free trade and protectionist government.

occurred when no yield improvements were made, while high yield gains caused around a 0.5% expansion in arable use. These results run counter to the desired outcome of freeing land from agriculture to allow for other GHG mitigating uses (Williams et al., 2018). In a study of agricultural intensification and changes in cultivated areas, 1970–2005, Rudel et al. (2009) found that in some cases intensification did lead to an expansion of cultivated land, which supports the BLUES model's findings.

There are several reasons why the changes in modelled agricultural land use proportions occurred. In the BLUES model, when a fall in income exceeds the tolerance level of landowners, they will switch to another use. In the model, the international price of arable crop is lower than the domestic price of arable crop and arable crop is imported. These imports force down the price of the domestic arable crop. On marginal, grade 3 land, when yields do not improve, or where they improve at a moderate rate, the additional crop volume cannot make up for falling income due to lower prices. When this occurs, marginal arable land is converted to pasture. In this respect, the model mimics a real effect seen previously in England. The effect of cheap imports of grain resulted in a steep decline in English wheat prices and production and a consequential loss of arable land from 1870 up to the period of the first World War (Venn, 1933). In the BLUES model, in scenarios where the yield of arable crop is increased, yield gains are initially able to counter falls in the domestic price of arable crop resulting from an increased supply, so despite price reductions, farm incomes are either maintained or improved at higher yields and arable land remains in arable production and also expands onto pasture. Additional factors which were not modelled could even lead to further arable expansion. For example, 'excess' crop production might be used for biofuels (Lotze-Campen et al., 2010) or farmers may engage in political lobbying asking for protective financial measures (Gawande & Hoekman, 2006; Monbiot, 2014). Also, incentives to change land use to different desirable uses, such as forestry, may be insufficient (Lawrence & Dandy, 2014). In such circumstances, an increase in arable yields will not spare land for this purpose.

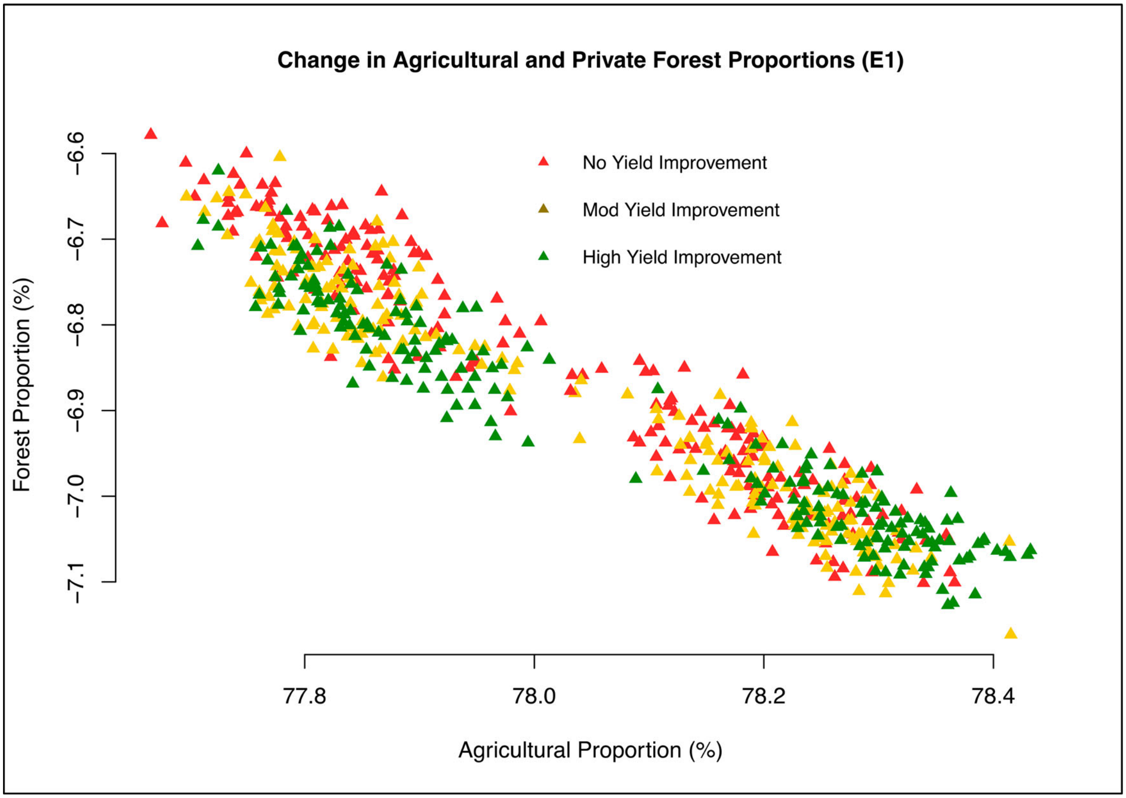

Figure 5. Shows the fall in private forest area against the rise in agricultural area (Arable and Pasture) for three yield scenarios in experiment 1.

While per-tonne livestock prices are always higher than those for crop, any increase in crop price which is greater than an increase in livestock price will gradually alter the balance in favour of arable expansion; particularly where this is coupled with crop yield gains. The change in agricultural land use is greater under a free trade government because this political ideology does not support domestic production through subsidy. Of the two agricultural land uses, arable production appears to be more vulnerable to loss of subsidy than livestock. This conclusion is reinforced by the model's results, as pasture land expanded in all scenarios and more so under a free trade government, where no subsidies apply. The BLUES model does not include tariffs that might be applied by a more protectionist government, and which if applied might result in less land use change and a more stable environment.

In all the scenarios, some land was abandoned. Land abandonment occurs when both the current use and alternatives result in an income lower than can be tolerated. Again, the absence of agricultural subsidy appears to have an effect as the amount of land abandonment from agriculture is slightly higher under the free trade scenarios. The abandonment of agricultural land could be positive from a GHG emission reduction perspective (Norbert & Bernhard, 2010), particularly where land reverts to scrub and moorland.

In England and Wales, the law prohibits forest clearance for farming (GOV.UK, 2018a). These rules, a key structural assumption, are absent from the BLUES model, which explains, in part, the forest losses. In all the scenarios, the proportion of land under agriculture (pasture and arable) expanded and in all cases the proportion of land under pasture increased, regardless of any increase or decrease in the proportion of arable land. Both agricultural and pasture expansion came at the expense of private and farm-forestry land, the proportions of which always fell. BLUES demonstrates that in absence of protection and incentives, private forests and farm-forestry are vulnerable to clearance and will not be replanted. While in practice a reduction in the proportion of private forests and farm-forestry is less likely to happen, it is not impossible. An expansion of forest grazing through pseudo-agroforest schemes or the loss of woodland to fire, wind, pests and disease as the result of climate change is possible (Ray et al., 2010).

The lack of woodland expansion occurs through different mechanisms; these result from the way afforestation and re-planting are valued and funded. In the model, landowners make income comparisons. These comparisons are based on several income options. The income option calculations are based on standard economic valuations commonly employed by land economists (Millington, 1984; Prag, 2003; RICS, 2007). These valuations highlight the loss of land value, the cost of planting and the 25-year gap between planting expenditure and income generation. This is compounded using discounted revenues. The process is a disincentive to afforestation and re-planting. In the model landowners are unlikely to plant new woodland and would rather abandon or convert felled woodland to pasture.

In both England and Wales, grants are currently available to landowners who switch from either arable or pasture use (GOV.UK, 2018b) but these were not included in the model. If both grants and legal protection of forests were included, areas already in private and farm-forestry would be expected to remain and depending on the level of grants, it is possible that some areas of pasture may have become afforested. In practice, this would only have occurred if incentives are sufficient; which currently they are not (Lawrence & Dandy, 2014). The BLUES model could be adapted to test levels of grant subsidy required to achieve large scale expansion of forests. Had the forestry factors above been included in the model, it is likely that the forest proportion would remain relatively static, with areas of arable and pasture expanding and contracting at the expense of the other.

In all the dietary and waste reduction scenarios, the proportion of arable and private farm-forestry land fell while the proportion of land under pasture and land abandonment grew. Change to the proportions of arable and pasture was least when consumers adopted a diet consisting of low meat and dairy consumption. This can be explained from a landowner income perspective as the fall in the rate of demand-increase affected both pasture and arable farming. The greatest changes to proportions of arable and pasture land occurred when consumer waste was reduced. Less waste causes a reduction in the rate of demand increase, which disproportionally affects arable cropping as arable cropping is more price and volume sensitive. Adding dietary changes of low meat and dairy consumption to a reduced waste scenario, lessened the magnitude of change in the proportions of land use. It has been shown that land-saving through yield increases can be offset by both population growth and dietary change and that dietary change may have a greater influence on agricultural land requirements than population growth (Kastner et al., 2012). Overall by the end of the modelled period, there was less arable land and more pasture and private and farm-forestry land cover under the dietary change scenarios than under the increased arable yield scenarios, indicating that in the BLUES model, dietary change produced a stronger effect on land use than crop yield improvement.

In all cases, a decrease in the consumption of meat and dairy led, surprisingly, to an increase in the proportion of pasture. The are several reasons for this. In all dietary scenarios, no allowance is made for crop yield improvement. Although domestic demand for arable crop does increase, crop prices are still depressed by imports. In this situation, livestock farming remains competitive especially on the marginal arable areas of grade 3 land. In the model, the difference between arable yields from the highest grade 1 land to the lowest grade 3 land is not as great as the difference between livestock yields on the same grades, meaning a change in land grade has a much greater impact on livestock production than crop production. In the model, livestock production volumes are also much lower than crop, while livestock prices are considerably higher. The import of livestock does not depress prices sufficiently to make livestock farming uncompetitive with arable. The relatively robust nature of pasture and the reduction of arable farming on marginal arable land, particularly in free trade situations in England has been observed and recorded before, between the years 1870 and 1931, by Venn (1933).

There is debate on the degree and effectiveness of free markets (Peterson, 2019) and how free markets impact food security, the environment and sustainability (Bureau et al., 2019; James, 2006). In the BLUES model, the governmental agent held one of two possible trade ideologies and acted either as a more protectionist government or as a free trade-oriented government. The former uses subsidy to support farmers and export restrictions to ensure food security, whilst the latter lets market forces decide both prices and availability of food. In the BLUES model, the protectionist government does not exercise the full ambit of protectionist policies; for example, tariffs and import restrictions are not modelled. Despite this, it is found that a distinct and significant difference exists between the two trade regimes. This affects both differences in the proportion of land use change and the number of times land use is changed. For any given scenario, both the proportion of land use change and the number of land use changes made is greater under the free trade regime. This suggests that the free market engenders less stability, from a land use perspective, than a protectionist policy orientated regime. This has implications for both agricultural business, society and the environment.

Sumner (2008) who describes farm subsidies as having a damaging effect on international trade, citing Gardner (1992) and Wright (1995) claims economists have found no evidence for many of the arguments made for agricultural subsidy, such as the claim that it improves financial stability. On the other hand, Soliwoda (2016) finds that the impact of the Common Agricultural Policy in the European Union had a stabilizing effect on level of farm income. This stabilizing effect can be inferred from the BLUES model's results because land use change is less frequent when a subsidy is applied. In the model, unsatisfactory incomes cause landowners to switch land use more often and unsatisfactory incomes occur more often when subsidies are absent. On the other hand, the net effect of farm specific subsidy, while creating more stability, might also be a disincentive to landowners considering switching to alternative uses.

Agricultural decision making is at least a yearly commitment, and as such it is not as responsive to price changes as other types of business. The flexibility afforded by arable cropping and livestock husbandry is, however, considerably greater than some land use alternatives, for example, forest planting which represents a commitment that can extend for several decades. One proposed GHG mitigation measure is afforestation (Rounsevell & Reay, 2009). Afforestation has been found to provide a relatively low-cost option for carbon sequestration (Nijnik et al., 2013). Forest planting is problematic because it is unlikely to produce income within the first 20–30 years after planting (Williams, 1988). Added to this there is also the cost of planting and protecting the young trees. The upfront cost is reflected in the loss of underlying land (solum) value while the effect of time is portrayed in the calculation of future income (Prag, 2003; Williams, 1988).

The loss of land value and the discounting of future returns were factored into the BLUES model. The model showed that tree planting would not emerge as a natural option for landowners. This suggests that to encourage tree planting some form of financial incentive might be appropriate; for example, carbon sequestration payments. Dumortier (2013) found while modelling forest planting through carbon payments that farmers delayed their decisions to plant trees by years until they gained more information about the evolution of carbon pricing. Ryan et al. (2015) found in a study of Irish farmers that while some farmers would plant trees if sufficient financial incentives were available, others would not, and that 'negative cultural attitudes' were sometimes 'stronger than financial drivers'. These issues of culture, risk and flexibility demonstrate that modelling simple rational financial decisions are inappropriate. In this respect, an ABM like the BLUES model with satisficing landowner agents whose behaviour is affected by their peers and hold a range of risk profiles and who do not act (economically) rationally, may be more useful.

5. Conclusions

Land use in England and Wales is less sensitive to the projected import price of goods than to other factors, such as arable yield increases, dietary change, waste reduction and security sensitivity as a product of political ideology. Waste minimization was a more effective driver than dietary change in changing proportions of agricultural land use. A protectionist regime kept both the proportion of land use change and the rate of change to a minimum as a policy of subsidy and export control stabilized incomes to a greater extent than the free trade approach. This stabilization of income is effective when landowners are satisficing. In all the scenarios, projected pasture expanded because it was a robust alternative to both crop production on marginal land and to forestry. In the absence of protection measures, this occurred at the expense of forest land. An expansion of pasture livestock farming is contrary to conditions required to mitigate GHG emissions. Forestry is recognized as a superior GHG mitigating alternative but was not an option adopted by landowner agents due to the high upfront costs of afforestation and intermittent income streams.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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James Reilly is a PhD student at the University of Aberdeen. His thesis was titled: An agent-based model to study past and future agricultural land use in England and Wales. Prior to his PhD James was a senior consultant with the Scottish Agricultural College and has work in land use, agriculture and forestry for 35 years. James has an MSc in Strategic Studies where he researched food security, an MSc in Land Economics where he researched the economics of carbon sequestration payments as a tool for afforestation. James has been a member of the Institute of Chartered Foresters for 23 years.

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References

Allouche, J. (2011). The sustainability and resilience of global water and food systems: Political analysis of the interplay between security, resource scarcity, political systems and global trade. *Food Policy*, *36*(1), S3–S8. https://doi.org/10.1016/j.foodpol.2010.11.013

Ang, J., Banerjee, R., & Madsen, J. (2010). Innovation, Technological Change and the British Agricultural Revolution. CAMA Working Paper No. 11/2010. [Online] Available at: https://ssrn.com/abstract=1668132 or http://dx.doi.org/10.2139/ssrn.1668132 [Accessed 3 Jul 2019].

Balmford, A., Amano, T., Bartlett, H., Chadwick, D., Collins, A., Edwards, D., Field, R., Garnsworthy, P., Green, R., Smith, P., Waters, H., Whitmore, A., Broom, D., Chara, J., Finch, T., Garnett, E., Gathorne-Hardy, A., Hernandez-Medrano, J., Herrero, M., … Eisner, R. (2018). The environmental costs and benefits of high-yield farming. *Nature Sustainability*, *1* (9), 477–485. https://doi.org/10.1038/s41893-018-0138-5

Balmford, A., Green, R., & Scharlemann, J. (2005). Sparing land for nature: Exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology*, *11*(10), 1594–1605. https://doi.org/10.1111/j.1365-2486.2005.001035.x

Bendor, J., Kumar, S., & Siegel, D. (2009). Satisficing: A 'pretty good' heuristic. *The B.E. Journal of Theoretical Economics Advances*, *9*(1), 2009. doi:10.2202/1935-1704.1478

Briassoulis, H. (2008). Land-Use policy and planning, theorizing, and modeling: Lost in translation, found in complexity? *Environment and Planning B: Planning and Design*, *35*(1), 6–33. https://doi.org/10.1068/b32166

Bureau, J., Guimbard, H., & Jean, S. (2019). Agricultural Trade liberalisation in the 21st century: Has It done the business? *Journal of Agricultural Economics*, *70*(1), 3–25. https://doi.org/10.1111/1477-9552.12281

Cain, P. (1980). *Economic foundations of British overseas expansion, 1815-1914*. The MacMillan Press Ltd.

Clark, M., & Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, *12*(6), 1–11. https://doi.org/10.1088/1748-9326/aa6cd5.

Defra. (2005). Yields of UK crops and livestock: physiological and technological constraints, and expectations of progress to 2050. Final Report on Defra Project IS0210, London: Defra.

Defra. (2008). *Ensuring the UK's food security in a Changing world.*

Defra. (2010). UK Food Security Assessment. [Online] Available at: http://webarchive.nationalarchives.gov.uk/20130402191230/http://archive.defra.gov.uk/foodfarm/food/pdf/food-assess100105.pdf [Accessed 18 Mar 2018].

Defra. (2014). Food security - Environment, Food and Rural Affairs Committee. [Online] Available at: https://publications.parliament.uk/pa/cm201415/cmselect/cmenvfru/243/24305.htm [Accessed 18 Sep 2018].

Defra. (2018). National Statistics Food Statistics in your pocket 2017 - Global and UK supply. [Online] Available at: https://www.gov.uk/government/publications/food-statistics-pocketbook-2017/food-statistics-in-your-pocket-2017-global-and-uk-supply [Accessed 27 Jul 2019].

Defra. (2019). *Agriculture in the United Kingdom*.

de Ruiter, H., MacDiarmid, J. I., Matthews, R. B., Kastner, T., & Smith, P. (2016). Global cropland and greenhouse gas impacts of UK food supply are increasingly located overseas. *Journal of The Royal Society Interface*, *13*(114). doi:10.1098/rsif.2015.1001

de Ruiter, H., MacDiarmid, J. I., Matthews, R., Lynd, L. R., Kastner, T., & Smith, P. (2017). Total agricultural land footprint associated with UK food supply 1986–2011. *Global Environmental Change*, *43*, 72–81. https://doi.org/10.1016/j.gloenvcha.2017.01.007

Dumortier, J. (2013). The effects of uncertainty under a cap-and-trade policy on afforestation in the United States. *Environmental Research Letters*, *8*(4), 1–11. https://doi.org/10.1088/1748-9326/8/4/044020

Food and Drink Federation. (2019). Export Snapshot. [Online] Available at: https://www.fdf.org.uk/exports/ukexports-2018.aspx [Accessed 29 Jul 2019].

Forest Research. (2019). Woodland Statistics. [Online] Available at: https://www.forestresearch.gov.uk/tools-and-resources/statistics/statistics-by-topic/woodland-statistics/ [Accessed 05 Jul 2019].

Gardner, B. (1992). Changing Economic Perspectives on the farm problem. *Journal of Economic Literature*, *30*(1), 62–101. Accessed March 29, 2021 http://www.jstor.org/stable/2727879

Garnett, T. (2007). Meat and Dairy Production & Consumption Exploring the livestock sector's contribution to the UK's greenhouse gas emissions and assessing what less greenhouse gas intensive systems of production and consumption might look like Working paper produced a part of the work of the Food Climate Research Network. [Online] Available at: https://www.fcrn.org.uk/sites/default/files/TGlivestock_env_sci_pol_paper.pdf [Accessed 05 May 2019].

Gawande, K., & Hoekman, B. (2006). Lobbying and Agricultural Trade Policy in the United States. [Online] Available at: http://www.cepr.org/active/publications/discussion_papers/dp.php?dpno=5634 [Accessed 05 Oct 2017].

Gilady, L. (2018). *The price of prestige: Conspicuous consumption in International relations*. The University of Chicago Press.

Gilpin, R. (1981). *War and change in world politics* (1st ed.). Cambridge University Press.

Godfray, C., & Garnett, J. (2014). Food security and sustainable intensification. [Online] Available at: http://dx.doi.org/10.1098/rstb.2012.0273 [Accessed 26 Nov 2016].

The Good Taste Guardian BV. (2018). Nutrition table.com. [Online] Available at: http://www.foodnutritiontable.com [Accessed 05 May 2018].

GOV.UK. (2018a). Tree felling licence: when you need to apply. [Online] Available at: https://www.gov.uk/guidance/tree-felling-licence-when-you-need-to-apply [Accessed 9 Aug 2018].

GOV.UK. (2018b). Grants for creating woodland available all year round. [Online] Available at: https://www.gov.uk/governm ent/news/grants-for-creating-woodland-available-all-year-round [Accessed 9 Aug 2018].

Green, R., Milner, J., Dangour, A. D., Haines, A., Chalabi, Z., Markandya, A., Spadaro, J., & Wilkinson, P. (2015). The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. *Climatic Change*, *129*(1-2), 253–265. https://doi.org/10.1007/s10584-015-1329-y

Gunasekera, D. (2015). Food production: Cut food waste to help feed world. *Nature*, *524*(7566), 415–415. https://doi.org/10.1038/524415a

Hammond, M. (2009). *Thucydides: The peloponnesian War*. Oxford University Press.

Jaggard, K., Qi, A., & Ober, E. (2010). Possible changes to arable crop yields by 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 27 Sep, *365*(1554), 2835–2851. https://doi.org/10.1098/rstb.2010.0153

James, H. (2006). Sustainable agriculture and free market economics: Finding common ground in adam smith. *Agriculture and Human Values*, *23*(4), 427–438. https://doi.org/10.1007/s10460-006-9020-6

James Hutton Institute. (2017). Arable Agriculture. [Online] Available at: https://www.hutton.ac.uk/learning/exploringscotland/land-capability-agriculture-scotland/arable-agriculture [Accessed 03 May 2017].

Kastner, T., Rivas, M., Koch, W., & Nonhebel, S. (2012). Changing diets and consequences for land demand. *Proceedings of the National Academy of Sciences*, *109*(18), 6868–6872. https://doi.org/10.1073/pnas.1117054109

Kleanthous, A. (2009). Pigs and the Environment. Agriculture and Horticulture Development Board: Kenilworth, p. 72.

Knoema. (2019). World GDP Ranking 2018. [Online] Available at: https://knoema.com/nwnfkne/world-gdp-ranking-2018-gdp-by-country-data-and-charts [Accessed 05 Jun 2019].

Kurse, J. (2018). Estimating Demand for Agricultural Commodities to 2050. Pre-publication draft. [Online] Available at: http://www.globalharvestinitiative.org/Documents/Kruse%20-%20Demand%20for%20Agricultural%20Commoditites.pdf [Accessed 03 May 2018].

Lamb, A., Green, R., Bateman, I., Broadmeadow, M., Bruce, T., Burney, J., Carey, P., Chadwick, D., Crane, E., Field, R., Goulding, K., Griffiths, H., Hastings, A., Kasoar, T., Kindred, D., Phalan, B., Pickett, J., Smith, P., Wall, E., … Balmford, A. (2016). The potential for land sparing to offset greenhouse gas emissions from agriculture. *Nature Climate Change*, *6*(5), 488–492. https://doi.org/10.1038/nclimate2910

Law, B., Hudibug, T. W., Berner, L. T., Kent, J. J., Buotte, P. C., & Harmon, M. E. (2018). Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences*, *115*(14), 3663–3668. https://doi.org/10.1073/pnas.1720064115

Lawrence, A., & Dandy, N. (2014). Private landowners' approaches to planting and managing forests in the UK: What's the evidence? *Land Use Policy*, *36*, 351–360. https://doi.org/10.1016/j.landusepol.2013.09.002

Lockwood, M. (2013). The political sustainability of climate policy: The case of the UK climate change Act. *Global Environmental Change*, *23*(5), 1339–1348. https://doi.org/10.1016/j.gloenvcha.2013.07.001

Lotze-Campen, H., Popp, A., Beringer, T., Müller, C., Bondeau, A., Rost, R., & Lucht, W. (2010). Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. *Ecological Modelling*, *221*(18), 2188–2196. https://doi.org/10.1016/j.ecolmodel.2009.10.002

Marvuglia, A., Gutiérrez, T., Baustert, P., & Benetto, E. (2018). Implementation of Agent-Based models to support life cycle assessment: A review focusing on agriculture and land use. *AIMS Agriculture and Food*, *3*(4), 535–560. https://doi.org/10.3934/agrfood.2018.4.535

Mercure, J., Pollitt, H., Bassi, A. M., Viñuales, J. E., & Edwards, N. R. (2016). Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Global Environmental Change*, *37*, 102–115. https://doi.org/10.1016/j.gloenvcha.2016.02.003

Millington, A. (1984). *An introduction to property valuation* (2nd ed). Estates Gazette.

Monbiot, G. (2014). The farming lobby has wrecked efforts to defend our soil. [Online] Available at: https://www.theguardian.com/environment/georgemonbiot/2014/jun/05/the-farming-lobby-has-wrecked-efforts-to-defend-our-soil [Accessed 07 July 2015].

Msangi, S., & Rosegrant, M. (2012). World agriculture in a dynamically changing environment: iFPri's long-term outlook for food and agriculture. In P. Conforti (Ed.), *Looking ahead in world food and agriculture: Perspectives to 2050* (pp. 57–88). FAO.

Natural England. (2012). Agricultural Land Classification: protecting the best and most versatile agricultural land (TIN049). [Online] Available at: http://adlib.everysite.co.uk/adlib/defra/content.aspx?id=2RRVTHNXTS.95MLRXA9XLVWU [Accessed 08 Jan 2018].

Nijnik, M., Pajot, G., Moffat, A., & Slee, B. (2013). An economic analysis of the establishment of forest plantations in the United Kingdom to mitigate climatic change. *Forest Policy and Economics*, *26*, 34–42. https://doi.org/10.1016/j.forpol.2012.10.002

Norbert, R., & Bernhard, O. (2010). Reducing Ghg Emissions by Abandoning Agricultural Land Use on Organic Soils. Stuttgart- Hohenheim, Germany, International Agricultural Trade Research Consortium, Proceedings Issues, 2010: Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security.

ONS. (2017). Statistical bulletin: National Population Projections: 2016-based statistical bulletin. [Online] Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2016basedstatisticalbulletin [Accessed 10 May 2018].

Parliament UK. (2017). Bill documents — European Union (Notification of Withdrawal) Act 2017. [Online] Available at: https://services.parliament.uk/bills/2016-17/europeanunionnotificationofwithdrawal/documents.html [Accessed 30 Jul 2019].

Peterson, E. (2019). Free trade and protectionism in food and agriculture. In D. Kaplan (Ed.), *Encyclopaedia of food and agricultural ethics* (pp. 976–981). Springer.

Prag, A. (2003). *The valuation of Rural Property. A comprehensive guide to the appraisal of farms and estates* (2nd ed.). Pakard Publishing Limited.

Quested, T., Parry, A., Easteal, S., & Swannell, E. (2011). Food and drink waste from households in the UK. *Nutrition Bulletin*, *36*(4), 460–467. https://doi.org/10.1111/j.1467-3010.2011.01924.x

Rae, A. (2017). *A land cover atlas of the United Kingdom*. The University of Sheffield.

Ray, D., Morison, J., & Broadmeadow, M. (2010). *Climate change: Impacts and adaptation in england's woodlands*. Forestry Commission.

Reilly, J., Dawson, T. P., Matthews, R. B., Smith, P., Musk, C. C., Potts, J. N., Poggio, P., Salt, D., & Polhill, J. G. (2020). *The calibration and validation of a social and Biophysical Agent-Based model of land Use for England and wales*. Manuscript in preparation.

RICS. (2007). *Valuation of Rural property*.

Rindfuss, R. R., Entwisle, B., Walsh, S. J. A. L., Badenoch, N., Brown, D. G., Deadman, P., Evans, T. P., Fox, J., Geoghegan, J., Gutmann, M., Kelly, M., Linderman, M., Liu, J., Malanson, G. P., Mena, C. F., Messina, J. P., Moran, E. F., Parker, D. C., Parton, W., … Verburg, P. H. (2008). Land use change: Complexity and comparisons. *Journal of Land Use Science*, *3* (1), 1–10. https://doi.org/10.1080/17474230802047955

Rosen, S. (2005). *War and Human nature* (2nd ed.). Princeton University Press.

Rounsevell, M., & Reay, D. (2009). Land use and climate change in the UK. *Land Use Policy*, *26*(1), 160–169. https://doi.org/10.1016/j.landusepol.2009.09.007

Rudel, T. K., Schneider, L., Uriarte, M., Turner, B. L., DeFries, R., Lawrence, D., Geoghegan, J., Hecht, S., Ickowitz, A., Lambin, E. F., Birkenholtz, T., Baptista, S., & Grau, R. (2009). Agricultural intensification and changes in cultivated areas, 1970–2005. *Proceedings of the National Academy of Sciences*, *106*(49), 20675–20680. https://doi.org/10.1073/pnas.0812540106

Ryan, M., O'Donoghue, C., Upton, V., & Handgraaf, M. (2015). Heterogeneous Economic and Behavioural Drivers of the Farm Afforestation Decision 89th Annual Conference, April 13-15, 2015, Warwick University, Coventry, UK. Warwick, Agricultural Economics Society.

Scoones, I., Smalley, R., Hall, R., & Tsikata, D. (2019). Narratives of scarcity: Framing the global land rush. *Geoforum; Journal of Physical, Human, and Regional Geosciences*, *101*, 231–241. https://doi.org/10.1016/j.geoforum.2018.06.006

Silvey, V. (1994). Plant breeding in improving crop yield and quality in recent decades. *Acta Horticulturae*, *35*(355), 19–24. https://doi.org/10.17660/ActaHortic.1994.355.2

Simon, H. (1955). A behavioral model of rational choice. *The Quarterly Journal of Economics*, *69*(1), 99–118. https://doi.org/10.2307/1884852

Simon, H. (1956). Rational Choice and the structure of the environment. *Psychological Review*, *63*(2), 129–138. https://doi.org/10.1037/h0042769

Smith, P. (2013). Delivering food security without increasing pressure on land. *Global Food Security*, *2*(1), 18–23. https://doi.org/10.1016/j.gfs.2012.11.008

Soliwoda, M. (2016). The impact of the support instruments of the Common Agricultural Policy on economic and financial stability of farms in EU countries. *Acta Universitatis Lodziensis. Folia Oeconomica*, *2*(319), 99–116. https://doi.org/10.18778/0208-6018.319.07

Spink, J., Street, P., Sylvester-Bradely, R., & Berry, P. (2009). The potential to increase productivity of wheat and oilseed rape in the UK. [Online] Available at: http://appg-agscience.org.uk/linkedfiles/ADAS%20Report%20-%20Increasing%20Wheat%20%26%20OSR%20Productivity.pdf [Accessed 12 Apr 2018].

Strassburg, B. B. N., Latawiec, A. E., Barioni, L. G., Nobre, C. A., da Silva, V. P., Valentim, J. F., Vianna, M., & Assad, E. D. (2014). When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environmental Change*, *28*, 84–97. https://doi.org/10.1016/j.gloenvcha.2014.06.001

Sumner, D. (2008). Agricultural Subsidy Programs, The Concise Encyclopaedia of Economics. Library of Economics and Liberty. [Online] Available at: https://www.econlib.org/library/Enc/AgriculturalSubsidyPrograms.html [Accessed 2019 Sep 2019].

Sylvester-Bradley, R., Foulkes, J., & Reynolds, M. (2005). Future wheat yields: Evidence, theory and conjecture. In R. Sylvester-Bradley, & J. Wiseman (Eds.), *Yields of farmed species: Constraints and opportunities in the 21st century* (pp. 233–260). Nottingham University Press.

Thayer, B. (2004). Darwin and International Relations: On the Evolutionary Origins of War and Ethnic Conflict. Lexington (Kentucky): The University Press of Kentucky.

Thomson, A., Misselbrook, T., Moxley, J., Buys, G., Evans, C., Malcolm, H., Whitaker, J., McNamara, N., & Reinsch, S. (2018). Quantifying the impact of future land use scenarios to 2050 and beyond - Final Report, Edinburgh: Centre for Ecology & Hydrology.

UKGov. (2011). Cereals and Oilseeds Production Harvest. [Online] Available at: https://data.gov.uk/dataset/cereals_and_oilseeds_production_harvest [Accessed 21 Nov 2015].

UN. (2017). World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248., New York: United Nations, Department of Economic and Social Affairs, Population Division.

Venn, J. (1933). *The foundations of agricultural economics. Together with an economic history of British agriculture during and after the great War cambridge* (2nd ed). Cambridge University Press.

von Braun, J., Ahmed, A., Asenso-Okyere, K., Fan, S., Gulati, A., Hoddinott, J., Pandya-Lorch, R., Rosegrant, M. W., Ruel, M., Torero, M., van Rheenen, T., & von Grebmer, K. (2008). *High food prices: The what, who and how of proposed policy actions*. Policy Brief, IFPRI.

Welsh Government. (2019). Agricultural land classification: predictive map. [Online] Available at: https://gov.wales/agricultural-land-classification-predictive-map [Accessed 04 May 2019].

Westhoek, H., Lesschen, P. J., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., Grinsven, H., Sutton, M. A., & Oenema, O. (2014). Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change*, *26*, 196–205. https://doi.org/10.1016/j.gloenvcha.2014.02.004

Williams, M. (1988). *Decision-Making in forest management* (2nd ed). Research Studies Press Ltd.

Williams, D. R., Phalan, B., Feniuk, C., Green, R., & Balmford, A. (2018). Carbon storage and Land-Use strategies in agricultural landscapes across three continents. *Current Biology*, *28* (15), 2500–2505. https://doi.org/10.1016/j.cub.2018.05.087

Wood, S. (2013). Prestige in world politics: History, theory, expression. *International Politics*, *50*(3), 387–411. https://doi.org/10.1057/ip.2013.13

World Bank. (2019). World Bank Open Data. [Online] Available at: https://www.worldbank.org [Accessed 07 Jul 2019].

Wright, B. (1995). Goals and realities for farm policy. In D. Sumner (Ed.), *Agricultural Policy reform in the United States* (pp. 9–44). AEI Press.