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# Effect of Climate and Agricultural Land Use Changes on UK Feed Barley Production and Food Security to the 2050s

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Received: 9 August 2017; Accepted: 7 October 2017; Published: 29 October 2017

**Abstract:** Currently, the UK has a high self-sufficiency rate in barley production. This paper assessed the effects of projected climate and land use changes on feed barley production and, consequently, on meat supply in the UK from the 2030s to the 2050s. Total barley production under projected land use and climate changes ranged from 4.6 million tons in the 2030s to 9.0 million tons in the 2050s. From these, the projected feed barley supply ranged from approximately 2.3 to 4.6 million tons from the 2030s to the 2050s, respectively. The results indicate that while UK spring barley production will thrive under, and benefit from climate change, total land area allocated to barley production will ultimately determine self-sufficiency. Without expansion in the area of land and/or further significant increases in yields, the UK may face large deficits in domestic feed barley production and, for that matter, meat supply in the future. Hence, agricultural and food security policy needs to consider, principally, the effect of agricultural land use change on key crops, such as barley. Even though the UK can import feed barley or meat to address the deficits observed in this study, the question that needs to be addressed is where all that import will come from.

**Keywords:** land use change; climate change; feed barley; meat consumption; food security

## 1. Introduction

The UK Government defines food security as ensuring the availability of, and access to affordable, safe, and nutritious food sufficient for an active lifestyle, for all, at all times [1]. Meat and animal products are a rich source of high value protein and essential micro-nutrients (iron, zinc, and vitamin A), and are therefore key to food security [2]. In this paper, food security is defined as “the risk of adequate food not being available” [3,4]; ‘food’ here refers to meat. Meat contributes a substantial proportion of daily calories in the UK diet.

By 2050, increase in population and incomes will combine with dietary shifts to raise meat consumption per person to about 49 kg for the world and 91 kg in high income countries, with total

meat demand in Europe and Central Asia projected to be 71 million tons [5]. To meet this demand, global meat production should be about 455 million tons [5], which will have a cascading effect on demand for animal feed. Globally, about 35% of total grain produced (the bulk of it being coarse grains) is used for animal feed [6]. Feed use constitutes about 52% and 54% of grains produced in the UK and the EU, respectively [2,7]. As a result of the projected meat demand, global cereal production will need to reach about 3 billion tons by 2050 to satisfy a projected animal feed demand of 1.1 billion tons and other end uses [5]. Feed use of cereal grains is projected to be 35 million tons for Europe and Central Asia [7]. Developing countries could import large quantities of coarse grains as they are projected to account for about 56% of global feed use of coarse grains by 2050 [5].

Globally, barley (*Hordeum vulgare*, L.) is the largest component of coarse grains used as animal feed [4]. By 2050, world barley production will have to increase by 54% over the level in the year 2000 to meet projected demand for food, feed, and industrial purposes [8]. Barley is the most important arable crop in Scotland and the second most important arable crop in the UK. Here, barley accounts for about 39% of feed use of grains and over 60% of total barley produced in the UK is used as animal feed [9]. In 2011, the UK produced 5.5 million tons of barley grains from 970,000 ha of land, with an average yield of 5.7 tons ha<sup>-1</sup> [9]. The long-term trend shows that the UK area of land for barley production has remained quite stable (with episodic increases) [9]. Similarly, meat (cattle, pig, chicken, and sheep) production in the UK has not varied substantially from 2005 to 2014 [10]. While the UK has self-sufficiency in barley production, it has a large trade deficit in meat and aggregate animal feed [9]. Recently, the cost of animal feed has become the largest item of expenditure on the agricultural production and income account in the UK due mainly to rising prices of cereals (which increased by 80% between 2005 and 2011) [9]. The cost of feed is projected to remain higher above long-term EU average due to the possible diversion of grains to bioenergy production [11]. At the same time, global demand for animal feed and meat is projected to increase substantially [5,7,8]. As an important source of grain for animal feed, barley plays a crucial role in UK's food security and it is important to assess whether future barley production would be sufficient to meet demand for animal feed. Land use and climate change will be key determinants of the scale of barley production in the future.

"Land use concerns the function or purpose for which the land is used by the local human population and can be defined as the human activities which are directly related to land, making use of its resources or having an impact on them" [12]. Changes in land use arise from competing economic, political, social, and environmental goals. Land use change is a major driver of current global existential and developmental challenges, including climate change, food security, biodiversity conservation, water security, energy sustainability, and poverty alleviation. In the UK, agriculture has the largest share of land use, with cereals (mainly wheat and barley) accounting for over 50% of cultivated lands [13]. Predictions of future agricultural land uses are characterized by great uncertainty [14,15]. Nevertheless, such predictions are useful in providing general conclusions about trajectories of future land use change [14]. Key findings of studies reviewed by Rounsevell and Reay [14] and Angus et al. [16] show: (a) general reductions in the area of croplands and increase in area of land for bioenergy crops and forest; (b) expansion of urban areas with changes in the spatial structure of urban growth and infrastructural networks for land-based transport; and (c) a loss of land in coastal areas. Thus, climate change mitigation and urban development goals will likely be major drivers of land use change and exert enormous pressure on croplands. At the farm scale, market and environmental conditions underpin farmers' decisions, which largely result in crop-specific land use changes [14]. In agro-ecosystems, land use change has direct consequences for the scale of food production and ecosystem services. Thus, the direction (increase or decrease) and intensity (magnitude of change per unit time and land use type) of agricultural land use changes in the UK will have considerable effects on the scale of cereal or barley production.

In northern temperate environments, such as the UK, studies show that projected climate change (changes in the concentration of atmospheric carbon dioxide, temperature, and precipitation) will be beneficial to C<sub>3</sub> cereal crops such as barley through increased photosynthetic capacity and, therefore,

biomass production and yield [17–19]. In addition, it has been reported that, despite potential temperature and water-related stresses, barley production in the UK would remain viable under projected climate change [19,20]. Just like other jurisdictions, studies on UK land use futures [14,16] have focused on aggregate changes in major land use types while climate change studies have focused on impacts on crop yields and risks (e.g., [19,20]). However, the interaction of climate change and land use change will substantially influence the scale of production of specific crops such as barley. Information on the effect of such interactions on cereal production and distribution of cereal crops to end uses for food security is limited. The current study aims to extend the existing literature on the interactive effects of land use and climate change on future food security by assessing the production and the intermediate role of a cereal crop in producing other food. Specifically, this study assesses the combined effect of projected changes in land use and climate change on UK barley production and the consequential effect on feed use of barley for meat production in response to projected demand to the 2050s. The central question being addressed is whether there will be sufficient feed barley supply from domestic production to meet projected demand without adversely affecting other end uses.

## 2. Materials and Methods

### 2.1. Current Barley and Meat Indices

The Food Balance Sheet (FBS), published by the Food and Agriculture Organization (FAO) of the United Nations, is widely used for national and international analysis of patterns of food supply and consumption because it is readily accessible and allows international comparisons [21,22]. The FBS provides a picture of the average supply and utilization of food items over a reference period of three years for a given country [21]. A detailed explanation of the components of the FBS is given by the FAO [21]. The FBS is useful for estimating shortages or surpluses of food, projecting future food needs and making policies regarding food production and trade [22]. Barley and meat indices (see Table 1A,B) were retrieved from the UK FBS [23] to represent the baseline. The proportionate domestic use and feed use of barley, as well as the proportionate feed barley in total feed grain, were considered representative for the calculation of future feed barley supply from total production. That is, it was assumed that these proportions would remain unchanged.

In this study, total meat consumption was based on bovine, mutton and goat, and poultry and pig meat. To assess the effect of future feed barley supply on domestic meat production or supply, the current total feed grain was equated to total meat production to allow the calculation of feed barley equivalent meat (FBEM) supply. Obviously, it is an overestimation to equate feed grain use to total meat produced. However, the idea underlying the approach adopted here is that this quantity of feed grain is required or used in the mix of diets to produce the stated total meat. In other words, the idea is to capture the proportional contribution of feed grains to meat production, albeit implicitly, rather than saying that meat is produced only with feed grains. The FBEM (Equation (1)) is, therefore, the quantity of meat (tons) that can be produced or supplied per unit feed barley supplied or consumed (as part of total mix of feed):

$$FBEM (tons) = \frac{y}{x}.z \quad (1)$$

where  $y$  is the quantity of feed barley in total feed grain (tons);  $x$  is the total feed grain (tons) and  $z$  is the total domestic meat production (tons). The result of the equation above was divided by the amount of feed barley supply to obtain a constant value that relates unit feed barley required for unit meat production in the future. In this study, feed barley was considered to be used in the production of meat only; the production of milk and eggs was excluded. This was meant to simplify and focus the study. It is true that the production of milk and eggs make substantial use of animal feed made from grains. However, eventually, spent dairy cows and layers are used as meat and thereby contribute to total meat production. Further, different animals for meat production have different feed requirement (in terms of composition and quantity) and feed use efficiencies [24,25]. Again, to simplify the study, it was

assumed that the proportions of feed barley required in the feed of the different animals considered in the current study would remain unchanged in the future.

**Table 1.** (A) Metrics on barley production and use derived from the UK Food Balance Sheet; and (B) metrics on meat production and use derived from the UK Food Balance Sheet. Data taken from FAOSTAT [23].

(A)		
Item Number	Description	Value
(1)	Total domestic production	5964 thousand tons
(2)	Total export	633 thousand tons
(3)	Total import	115 thousand tons
(4)	Total supplied for domestic use	4953 thousand tons
(5)	% domestic use	(5) = [(4)/(1)] × 100 = 83.0%
(6)	Total supplied for animal feed	3037 thousand tons
(7)	% feed use	(7) = [(6)/(4)] × 100 = 61.3%
(8)	Total supplied for brewing and distilling (considered collectively as 'malt use')	1713 thousand tons
(9)	% malt use	(9) = [(8)/(4)] × 100 = 34.6%
(10)	Self sufficiency	(10) = [(1)/(4)] × 100 = 120.4%
(11)	Per capita barley use	(11) = [(4)/total population] = 80 kg year <sup>-1</sup>
(12)	Per capita feed barley	(12) = [(6)/total population] = 49 kg year <sup>-1</sup>
(13)	Proportion of feed barley in total feed grain *	38.5%
(14)	Per capita feed grain	153.5 kg year <sup>-1</sup>
(B)		
Item Number	Description	Value
(1)	Total domestic production	3.5 million tons
(2)	Total export	695 thousand tons
(3)	Total import	2.4 million tons
(4)	Per capita consumption	84.2 kg year <sup>-1</sup>
(5)	kcal supplied per capita per day	457

\* Total feed grain (sum of all cereal grain used as animal feed) was represented by wheat and barley used as animal feed since they contributed 96% of all feed use of grains, with oats contributing only 2%. Hence, total feed grain comprised 61.5% wheat and 38.5% barley. Total UK population on the FBS was 61,887,000 people [23].

## 2.2. The Future Situation

### 2.2.1. Climate Change and Barley Grain Yields

The Intergovernmental Panel on Climate Change (IPCC) has defined four main families of emission scenarios (A1, A2, B1, and B2; with subdivisions) which are narratives of potential trajectories of greenhouse gas (GHG) emissions as a result of certain assumptions on different socio-economic conditions and development pathways over the course of the 21st century [26]. The UK Climate Projections 2009 (UKCP09) is a publicly accessible online database that provides data on projected climate change (relative to a baseline period of 1961–1990) over the UK [27]. In the UKCP09, three emission scenarios are used: the A1FI, A1B, and B1 (also referred to as high, medium, and low emission scenarios, respectively). Briefly, the A1 narrative represents a future world characterized by very rapid economic growth, rapid availability of new and efficient technologies, fast decline in regional economic disparities and with global population peaking at 8.7 billion in 2050 and declining thereafter to 7.1 billion by the end of this century. The A1 scenario has three subdivisions: A1FI (representing intensive use of fossil fuels), A1T (representing intensive use of non-fossil energy sources), and the A1B (representing an intermediate situation between A1FI and A1T). The B1 narrative portrays a future world inclined towards global equity and sustainable solutions to economic, social and environmental challenges. It also assumes rapid structural shifts towards service and information oriented economies, as well as clean and efficient technologies with less intensive material use. The B1 narrative has the same population scenario as the A1 narrative [26].

Projected daily climate data for the 2030s, 2040s, and the 2050s under the low, medium, and high emissions scenarios (LES, MES, and HES) were obtained from the UKCP09 using the embedded Weather Generator (WG, version 2). Details of the UKCP09 and the WG are provided in Murphy et al. [27] and Jones et al. [28], respectively. The WG randomly samples a specified number of model variants from the probabilistic projections and uses a stochastic process to generate statistically credible daily or hourly future climate variables at 5 km resolution [28]. The generated future climate data, together with data on hydraulic properties of soils obtained from the Crop Growth Monitoring System (CGMS) database in the New Soil Information System (SINFO) used for agricultural monitoring in the European Union [29], and information on growth of the spring barley genotype 'Westminster', were used to simulate future barley grain yields for each of the time slices and emissions scenarios. The HGCA Recommended List shows that the genotype Westminster is widely grown in the UK, both as spring and winter barley crop for feed and malt, and is high-yielding. The AquaCrop model [30] was used for the simulations. The AquaCrop model was calibrated using field data from the genotype Westminster grown in 2011 in Dundee (south-east Scotland), information provided in Raes et al. [30], and personal communications with scientists at the James Hutton Institute, Dundee. Further, for the climate change simulations, the ability of AquaCrop to predict barley yields in the baseline period and uncertainties associated with sowing dates were further evaluated by forcing the model (through parameter adjustment) to predict the 1990 yields. To test or validate the goodness of the sowing dates and the model setup, the prediction error of the model was assessed by comparing simulated and observed yields for the baseline period (1980–1989) using the root mean square error (RMSE). With good sowing dates identified, simulations of future yields were done. All simulations were done for rain-fed conditions for the 14 UK administrative regions but the national average is used in this paper. With the exception of Wales, the RMSE values for the baseline simulations for all UK regions were under 1 ton ha<sup>-1</sup> [20]. Further details of the simulations can be found in [20].

### 2.2.2. Land Use Change and Barley Production

The projected areas of UK arable crops for the 2030s, 2040s, and 2050s were taken from Thomson et al. [31]. This was the report of a study conducted for the Department of Energy and Climate Change (DECC). The projections in this report were based mainly on likely policy goals and directions in the nexus of energy, food and climate change [31]. Thomson et al. [31] divided the land use, land use change, forestry (LULUCF) sector into six land use categories: forest land, cropland, grassland, wetlands, settlements, and other land. Four scenarios were constructed (business as usual, low, mid, and high) based on the UK land use policy priorities and aspirations such as targets on food production, reductions in greenhouse gas emissions, or achieving a given extent of forest cover by 2050 [31]. In the business as usual scenario, the current afforestation rate was maintained up to 2050 but other factors were similar to the mid scenario. The mid scenario represented land use change midway between the high and low scenarios. The low scenario focused on the production of bio-energy crops and afforestation. The high scenario prioritized food production with little emphasis on bio-energy crops and forestry [31].

For the current study reported in this paper, future areas of croplands were based on two main scenarios (business as usual and the policy-related land use change represented by the mid scenario provided in [31]), with additional eight scenarios which were adjustment of the policy-related land use change (mid scenario) to represent the effect of non-policy factors on land use change. In the business as usual (BAU) scenario, the average land area for barley production for the period 2000–2012 (1026 million ha) remains unchanged to 2050. The area of land under the BAU scenario constituted 16.36% of the average total area of arable crops for the period considered [32]. This proportion was assumed to remain unchanged to the 2050s and was used to calculate the area of land for barley production from projected cropland areas in Thomson et al. [31] for the three time slices. Thus, the area of land for barley for each future time slice was calculated as a proportion as indicated earlier. The high scenario in Thomson et al. [31] were not used because it significantly increased the area of

croplands and the UK's net greenhouse gas emissions. The low scenario was also not used because of the large increase in the area of bio-fuel crop production and was considered unlikely. Land use futures in the UK will likely be driven by policies sensitive to multifunctional land use and ecosystem services [33], with a balanced focus on energy security, climate change mitigation, food security, and environmental goals aimed at reducing the negative impacts of agriculture [2,16,33].

The remaining eight scenarios were aimed at incorporating possible crop-specific land use changes, in response to market forces and other non-policy factors. To this end, a range of changes from  $\pm 5$  to  $\pm 20\%$  (at 5% interval), was applied to the land areas under the mid scenario. This range was based on the calculated range of annual changes in the areas of land under barley cultivation over the period 2000–2012 [32], which was  $-19.41\%$  to  $14.94\%$ . To obtain the combined effect of climate change and land use change on future total barley production, the projected areas of land for barley production for each of the time slices and emissions scenarios were multiplied by their corresponding yields of barley from the climate change simulations.

### 2.2.3. Demand for Feed Barley and Meat

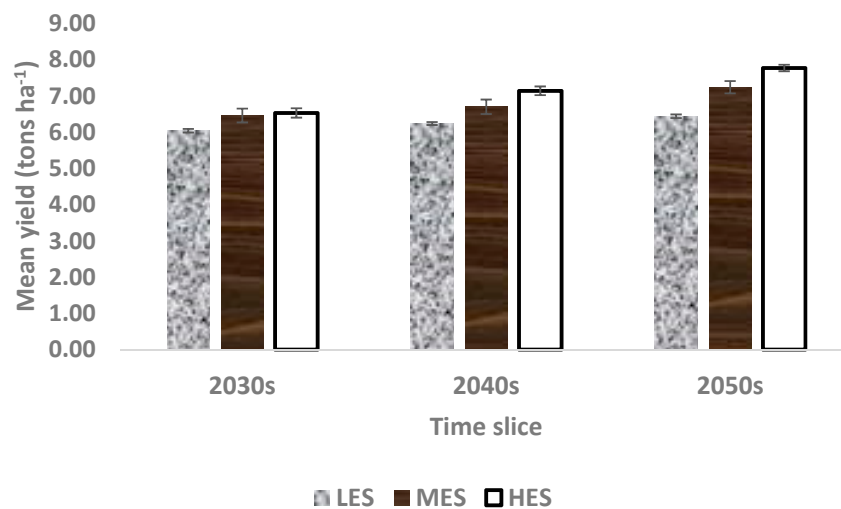
Different reports on projections of global food demand to 2050 exist (see, for example, [5,8,34,35]). In the current study, projected per capita demand for meat and feed grain were obtained from the Comprehensive Assessment of Water Management in Agriculture [34]. This particular study was used because it was the only report which explicitly provided future demand for feed grains. Unfortunately, this report compared future meat and feed grain demand between the OECD (Organization for Economic Co-operation and Development) countries and other regions but not on national basis. However, because it was difficult to obtain the required information for the UK, the projected per capita demand for meat and feed grain for the OECD was used to represent the UK. This has implications for the accuracy of the estimated future demand for meat and feed barley. The good news is that increases in aggregate meat demand in the OECD is expected to result mainly from population growth as changes in per capita meat consumption are projected to be marginal [5,6,25]. The values of meat and feed grain demand for 2025 were used to represent the 2030s and the average of the values for 2025 and 2050 were used to represent the 2040s.

The proportion of feed barley in total feed grain demand per capita was assessed to be 38.5% (see Table 1a) for each time slice. Subsequently, feed barley equivalent meat (FBEM) was calculated (see Equation (1)). Total meat and feed barley demands were then computed as the product of projected population (using the constant population growth scenario data obtained from the UK National Population Projections by the Office of National Statistics) and either per capita meat or feed barley demand. In population projections, the constant fertility scenario, unlike the high and low scenarios, assumes that the fertility rate for 1995–2000 remains unchanged through the future period of interest. The possible supply of barley for domestic uses was assessed to be 83% (see Table 1a) of future UK barley production under each land use scenario, time slice and climate change emission scenario. Similarly, potential malt and feed barley supplies were calculated as proportions of barley supply for domestic uses. Finally, the difference between the projected feed barley or meat demand and supply was calculated to show production deficit or surplus.

## 3. Results

### 3.1. Projected Barley Grain Yields

Mean grain yields under projected climate change were highest under the high emissions scenario (HES) in the 2050s and lowest under the low emissions scenario (LES) in the 2030s (Figure 1). For all emissions scenarios and time slices, the magnitude of yield was in the order HES > MES > LES. Differences in yields between the emissions scenarios followed the order 2030s < 2040s < 2050s. Mean yields for all time slices and emissions scenarios were higher than that of the baseline (4.24 tons ha<sup>-1</sup>).



**Figure 1.** Mean barley yields under the low, medium and high emissions scenarios (LES, MES, and HES, respectively) and three time slices. Error bars are standard errors. Source: authors' simulation results.

### 3.2. Projected Land Areas and Barley Supply for Domestic Use

For each time slice, the current (BAU) land area for barley production is greater than the projected areas of land under the Mid scenario and the Mid+5% (Table 2). The land areas under the Mid+10% to Mid+20% scenarios are greater than the BAU and all other scenarios. For all scenarios, areas of land for barley production range from 756,000 ha (Mid-20% scenario in the 2030s) to 1156 thousand ha (Mid+20% scenario in the 2050s).

**Table 2.** Projected areas of land for barley production in the UK. Mid land use scenario data obtained from Thomson et al. [31].

Land Use Scenario	Total Area for Barley Production ('000 ha)		
	2030s	2040s	2050s
BAU	1026	1026	1026
Mid	945	954	963
Mid+5%	992	1002	1011
Mid+10%	1040	1049	1059
Mid+15%	1087	1097	1107
Mid+20%	1134	1145	1156
Mid-5%	898	906	915
Mid-10%	851	859	867
Mid-15%	803	811	819
Mid-20%	756	763	770

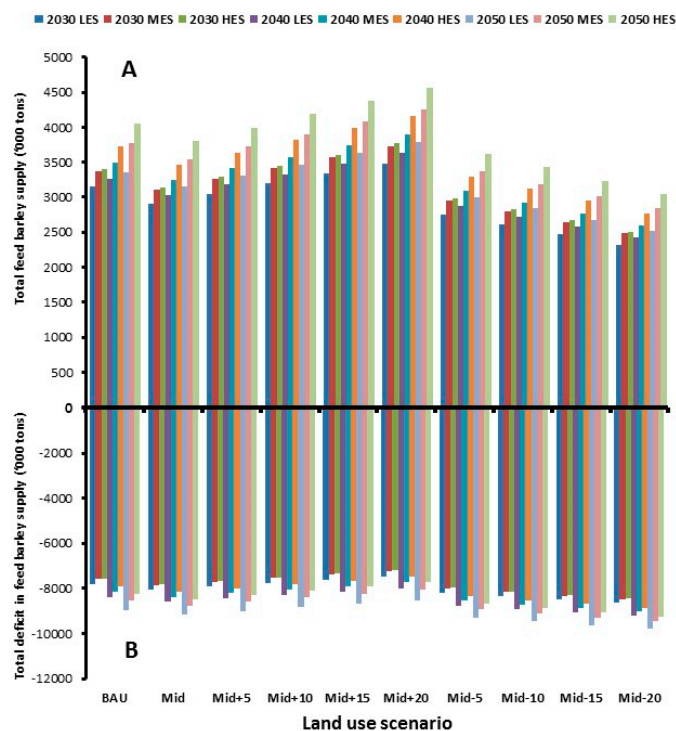
With the effects of climate change on yields, total barley production under the BAU scenario ranged from approximately 6.2 million tons in the 2030s (under the LES) to 8.0 million tons in the 2050s under the HES (Table 3). With the combined effects of projected changes in land area and the climate, projected total UK barley production ranged from approximately 4.6 million tons (under the low emission scenario, LES, and the Mid-20% scenario in the 2030s) to 9.0 million tons in the 2050s under the Mid+20% and the high emission scenario (HES) (Table 3). The difference between the maximum barley production for the BAU and Mid+20%, under the HES in the 2050s, is approximately 1.0 million tons.

**Table 3.** Projected total UK barley production due to land use and climate change. Data from authors’ simulations and calculations.

Land Use Scenario	Total Barley Production (‘000 tons)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	6197	6628	6700	6402	6874	7326	6607	7428	7972
Mid	5708	6105	6171	5953	6392	6812	6202	6972	7483
Mid+5	5993	6410	6479	6251	6711	7152	6512	7321	7857
Mid+10	6279	6715	6788	6548	7031	7493	6822	7669	8231
Mid+15	6564	7020	7096	6846	7351	7833	7132	8018	8605
Mid+20	6849	7326	7405	7144	7670	8174	7442	8367	8979
Mid-5	5422	5799	5862	5655	6072	6471	5892	6624	7108
Mid-10	5137	5494	5554	5358	5753	6130	5582	6275	6734
Mid-15	4852	5189	5245	5060	5433	5790	5271	5926	6360
Mid-20	4566	4884	4937	4762	5113	5449	4961	5578	5986

The potential barley supply for domestic uses shows the same pattern as the total production since the former is a constant proportion of the latter. The largest amount of projected barley supply for domestic uses was approximately 7.5 million tons in the 2050s, under the HES and Mid+20% scenarios; the lowest was 3.8 million tons in the 2030s under the LES and Mid-20% scenarios.

Similarly, projected feed barley supply from domestic production is a constant proportion of the barley supply for domestic use. Feed barley supply under the BAU ranged from approximately 3.2 million tons, in the 2030s to 4.1 million tons in the 2050s (Figure 2A). For the other scenarios, maximum feed barley supply ranges from approximately 3.5 to 4.6 million tons under the Mid+20% scenario, whereas the minimum supply ranges from approximately 2.3 to 3.0 million tons for the Mid-20% scenario.



**Figure 2.** (A) Projected UK feed barley supply from domestic production; and (B) projected deficits in UK feed barley supply from domestic production using the constant fertility scenario of population growth. Data from authors’ simulations and calculations.

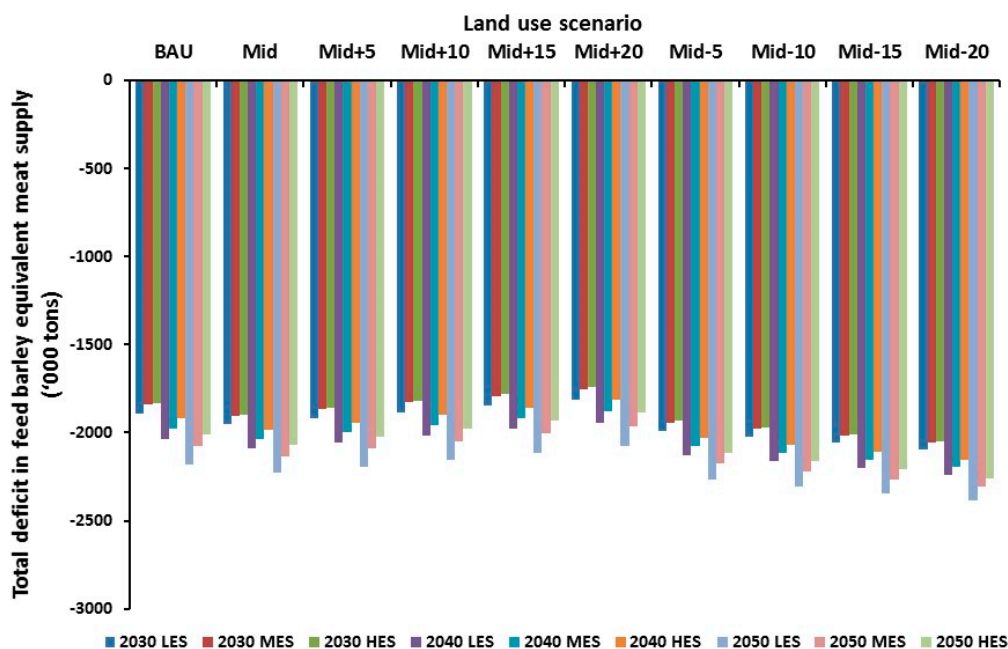


### 3.3. Projected Feed Barley and Meat Demand

Using the constant fertility scenario, UK population for the 2030s, 2040, and 2050 was estimated to be 71.9, 76.1, and 80.3 million, respectively (Office of National Statistics). The corresponding total meat demand values were 6902, 7344, and 7789 thousand tons, respectively, while total feed grain demand values were 28,472, 30,212, and 31,959 thousand tons, respectively (data not shown). Similarly, the total feed barley demand (as a proportion of total feed grain demand) was 10,962, 11,632, and 12,304 thousand tons, respectively, for 2030, 2040, and 2050. For the same time slices, the feed barley equivalent meat demand was 2657, 2827, and 2999 thousand tons, respectively.

Consequently, the projected ranges of deficits in UK feed barley supply from domestic production, for all land use and climate change scenarios, were approximately 7194 to 8639 thousand tons for the 2030s; 7473 to 9057 thousand tons for the 2040s; and 7736 to 9623 thousand tons for the 2050s (Figure 2B). The deficits under the BAU scenario ranged from 7553 (under the HES in the 2030s) to 8943 thousand tons (under the LES in the 2050s) while the values for the mid scenario ranged from 7822 (2030s) to 9149 thousand tons in the 2050s.

The corresponding deficits in total meat supply, for all scenarios, ranged from 1744 to 2094 thousand tons in the 2030s, 1816, to 2238 thousand tons in the 2040s, and 1886 to 2384 thousand tons in the 2050s (Figure 3). Under the BAU, the deficits ranged from 1831 (2030s) to 2180 thousand tons in the 2050s. The corresponding values for the mid scenario were 1896 to 2230 thousand tons, respectively.



**Figure 3.** Projected deficits in UK total meat supply due to deficits in feed barley supply using the constant fertility scenario of population growth. Data from authors' simulations and calculations.

## 4. Discussion

In general, increases in yield will continue to be a preferable path to increasing total production of crops for food security [7]. It is likely that the UK will continue to rely on domestic production as the main source of its feed barley supply. While the UK spring barley production would remain viable under climate change and benefit from yield increases over baseline yields (see Figure 1, [20]), the land area allocated to barley production will be the ultimate determinant of total production. The mid scenario suggests that policy-driven land use change might reduce the area of land for barley

production (relative to the BAU) by as much as 81, 72, and 63 thousand ha by the 2030s, 2040s, and 2050s, respectively. This will result in large reductions in total UK barley production.

In the UK, government policies have been the main driver of agricultural land use change in the past, with factors such as farm incomes, prices and land values playing secondary roles [2,16]. The UK's biofuel obligation under the EU Renewable Energy Directive (2009) and targets on reducing greenhouse gas emissions (as captured in the UK Climate Change Act 2008) might adversely affect agricultural land use futures through a suite of policy and legal instruments, financial and tax incentives, and market signals [36]. Some studies suggest very large areas of land would be required to meet the UK's bioenergy targets up to 2050 [37,38]. For example, the UK might require between 2.7 and 7 Mha of land to satisfy its biofuel needs by 2050 [37]. By the year 2020, biofuel crop production would likely shrink the area of land under barley production by 21% in the EU [11]. Thus, policies regarding climate change and bioenergy production might cause future reductions in the area of food crops and, for that matter, barley.

Similarly, non-policy or market-related factors can cause short term changes in total production through changes in the area of land allocated to barley production [16,39]. The results in the present study show that if these factors increase land area for barley by 20% over the projected level (mid scenario) and under the HES, the absolute increase in total feed barley supply, relative to the BAU, would be 359, 432, and 512 thousand tons for the 2030s, 2040s and 2050s, respectively (Figure 2A). The corresponding reductions in total production under the Mid-20% scenario are 897, 955, and 1010 thousand tons, respectively. Reductions in total barley production could affect the supply of barley for domestic uses or feed.

#### *4.1. Deficits in Feed Barley or Feed Barley Equivalent Meat Supply*

Currently, the UK is largely self-sufficient in barley production and almost all its feed barley is supplied from domestic production [9]. Based on the results in the present study, the UK might face large deficits in feed barley or feed barley equivalent meat supply under all land use and climate change scenarios (Figures 2B and 3). Population growth will principally account for increases in meat demand in high-income countries, such as the UK [5,6,25]. Projected increases in population and aggregate meat demand require substantial increases in land area allocated to barley production to offset the potentially large deficits in feed barley or feed barley equivalent meat supply. The difference between future demand and current feed use of barley (Table 1) are 8, 8.6, and 9.3 million tons, respectively, for the 2030s, 2040s, and 2050s. The corresponding feed barley equivalent meat demand for each future time slice is greater than the current quantity of meat imported to the UK. Such large deficits would require integration of policies to ensure a sound balance between domestic production and imports, while addressing the issues of population growth and meat consumption.

It is noteworthy, however, that different animals have different grain feed requirements and feed conversion efficiencies [24,25]. For instance, beef cattle require about five times the dietary energy required by poultry. Thus, the actual total feed barley that will be required in the future will also depend on the proportions of different types of meat that will be demanded. In the UK, a decline in the consumption of carcass meat (mainly beef and lamb) has been observed, while the consumption of non-carcass meat (poultry, pork, and processed meat) is either stable or increasing [9,32]. A similar observation has been made in the EU [11] and the USA [40]. However, this trend might change with improvements in the economy or the socio-economic conditions of consumers [11] due to different price and income elasticities of food components. For example, in the UK, while the average household expenditure on carcass meat is increasing, the average quantity purchased is decreasing [32]. Thus, the observed decline in absolute quantity of carcass meat consumption in the UK might be due to an inflationary effect, possibly through increase in the cost of animal feed [9], rather than a substantial switch to non-carcass meat as substitutes.

It has been suggested that import of meat and animal feed to Europe will increase substantially in the future [7,11]. This might occur through greater attention being given to bioenergy needs to the

detriment of feed use of grains to meet renewable energy targets [7,11,36]. As a result, it has been suggested that barley can lose about 21% of its total area of land in the EU to other biofuel cereals, such as soft wheat and maize [11]. Since the EU remains the largest source of meat and animal feed imports to the UK, the food security question that needs to be addressed is: where will the feed barley or feed barley equivalent meat come from to balance the large deficits observed in the current study? Further, it is important to assess the implications of the UK's exit from the EU for future imports of feed barley or meat to the UK.

#### 4.2. Limitations to the Study

Projections are not equivalent to forecasting or predicting the future, especially over long time horizons for which uncertainties are larger. Rather, projections provide a broad overview of the future state of what is being projected [2]. Hence, projections are not to be considered as prescriptions for the future, but as useful inputs for triggering discussions on alternative adaptive pathways to possible future states of the phenomenon under consideration. This notwithstanding, projections should be based on reasonable analysis of current practice or knowledge. However, finding fit for purpose data for coupled land use and climate change analysis is a challenge [33]. This paper has presented projections of future feed barley supply as affected by land use and climate change and its implications for food security via meat production in the UK. To achieve this, several assumptions had to be made and semi-empirical relationships derived from the current production and feed use of barley as well as meat production or consumption. These have implications for the results obtained in the current study. The proportionality assumption has been central to the current study. For example, one key assumption was that the proportion of feed use of grains (and for that matter barley) in the mix of feed for total meat production based on the animals considered in this paper would remain unchanged to the 2050s. Obviously, policy signals, environmental, market, and other socio-economic conditions can alter the proportional relationships in the future. As a result, the deficits in feed barley or meat production observed in the current study are conservative and applicable only to future conditions that fall within the limits of the current study. For example, the feed barley or meat demand could have been higher or lower, if the high or low fertility scenario of population projection had been used, respectively. In addition, simulations of effects of climate change on crop yields have uncertainties. In the current study, the error associated with the ability of the AquaCrop model to simulate future yields was less than 1 ton ha<sup>-1</sup> [20]. However, since error propagation was not done, it is possible that the projected yields could be higher or lower than the observed values used in the current study. Overall, within the limits of the current study, it can be deduced that future reductions in UK croplands would negatively affect feed barley and meat production. This would have a cascading effect on food security via excess demand for meat (due to population growth) over supply from domestic production. This provides a useful input to discussions about future feed use of cereals from domestic production and alternative sources of imports when necessary.

### 5. Conclusions

Future changes in agricultural land use in the UK will depend largely on the interactive effect of policies regarding food security, climate change and renewable energy. Non-policy factors (mainly market signals) will also affect short term changes in total area of land allocated to a particular crop. Even though climate change can be beneficial to UK barley grain yield, the total area of land allocated to barley will be the key determinant of the UK's future barley production. This study shows that the UK can face large deficits in feed barley or meat supply from domestic production in the future due mainly to inadequate area of land allocation to barley vis-à-vis the large demand due to population changes. As a result, the UK might need to import large quantities of feed barley or meat to balance the projected domestic deficits. Given the projected level of global and EU demand for meat and animal feed, the challenge remains in identifying where the imports to the UK might come from to balance the large deficits predicted in feed barley or feed barley equivalent meat. All things being equal, and

in lieu of large imports, the UK would need to substantially expand the area of barley production to offset potential food security risks. The UK would also need to tightly couple land use and food security policy goals to secure adequate production of key crops, such as barley.

**Acknowledgments:** This work was part of a PhD study jointly sponsored by the Centre for Environmental Change and Human Resilience (CECHR, University of Dundee) and The James Hutton Institute (JHI), and was supported by the Rural and Environment Science and Analytical Services Division (RESAS) of the Scottish Government through Work packages 3.3 and the Centre of Expertise in Climate Change (2011–2016).

**Author Contributions:** David O. Yawson, Barry J. Mulholland, Tom Ball, Sushil Mohan, and Philip J. White conceived and designed the study; David O. Yawson conducted the study under the supervision of Barry J. Mulholland, Tom Ball, Sushil Mohan, and Philip J. White. David O. Yawson and Michael O. Adu processed and analyzed the data; and David O. Yawson, Barry J. Mulholland, Tom Ball, Sushil Mohan, Michael O. Adu, and Philip J. White wrote the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

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