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Research article

Virtual water flows under projected climate, land use and population change: the case of UK feed barley and meat

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ABSTRACT

The flow of water through food commodity trade has been rationalized in the virtual water concept. Estimates of future virtual water flows under climate, land use, and population changes could have instrumental value for policy and strategic trade decisions. This paper estimated the virtual water flows associated with feed barley and meat imports to the UK under projected climate, land use, and population changes from the 2030s to the 2050s. The results show that future virtual water inflows associated with barley imports to balance domestic deficits are larger than total volume of water used in domestic barley production in the UK. Mean virtual water associated with total UK barley production ranged from 206 to 350 million m^3. This is much less than the mean total virtual water associated with barley imports (if total barley produced in the UK is used for feed), which ranged from 2.5 to 5.6 billion m^3 in the 2030s to the 2050s for all land use and climate change scenarios. If domestic barley production is distributed to the different end uses, the total virtual water inflows associated with imports to balance domestic feed barley supply could be as high as 7.4 billion m^3. Larger virtual water inflows (as high as 9.9 billion m^3) were associated with feed barley equivalent meat imports. While the UK barley production would be entirely green, imports of either barley or meat would result in large blue water inflows to the UK. Virtual water inflows increased across the time slices for all emissions scenarios, indicating weak effectiveness of yield or productivity gains to moderate virtual water inflows. While increase in yield and land allocated to barley production should be adaptive targets, the UK needs to take policy and strategic actions to diversify trade partners and shift imports away from countries where blue water flows can exacerbate existing or potential water stresses.

1. Introduction

'Virtual water' refers to the volume of water used in producing a given quantity of food commodity that is traded (Allan, 1998; 2003). The volume of water per unit mass of the food commodity is the virtual water content of that food commodity. With primary crop commodities, virtual water content refers principally to the ratio of total volume of water lost to evapotranspiration and the yield. This definition excludes the small amount of water retained in the plant cells during growth or in the harvested product (Hess, 2010), water used in agronomic management activities such as application of chemical inputs (e.g. fertilizers and pesticides) (Berger and Finkbeiner, 2010; Ridoutt and Pfister, 2010), or water used in cleaning equipment, washing produce and by farm workers (Hess, 2010). These can be accounted for in water footprint studies (Berger and Finkbeiner, 2010). The virtual water content of the food commodity is considered as embodied in the commodity and, hence, importing countries 'virtually' gain (or save) the volume of water used to produce the quantity of food commodity imported (Allan, 2003). Conversely, the exporting nation loses that volume of water used to produce the given quantity of the food commodity traded. The instrumentality of virtual water for addressing water and food insecurity concurrently stems from its inherent proposition that a given economy

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can offset its water scarcity and maintain food security through the importation of water-intensive food commodities (Yawson et al., 2013; Dalin et al., 2012; El-Sadek, 2011; Aldaya et al., 2010; Hoekstra, 2010; Chapagain and Hoekstra, 2008). Virtual water provides an avenue for integrating the food system and the hydrological system in a single analytical and management framework to inform trade and resource management decisions and actions. While there have been arguments from both proponents and opponents on the utility of virtual water for water-food security, virtual water can be instrumental for addressing global water and food security concerns in the future due to the adverse impacts of climate change on water availability and food production. To achieve this, however, Yawson et al. (2013) suggested that virtual water flows should be agri-compatible.

Water and food production are intricately linked. Globally, agriculture has the largest share of land use (Foley et al., 2011), and is the most water intensive human activity in the world (de Fraiture and Wichelns, 2010; Molden, 2007). For crops, water is required for photosynthesis, nutrient uptake, yield formation, and realization of yield potential. For example, yield formation in cereals (which are water-intensive crops) is primarily regulated by water availability (Rajala et al., 2011; Barnabas et al., 2008; Araus et al., 2002). Hence, future food production or security will depend considerably on water availability, but it is not easy to readily answer the question 'how much water will be required to satisfy future food demand?'

However, projections suggest that future food demand and supply will be dictated, principally, by the joint or independent effect of climate, population, and land use changes. Climate change is expected to have varying effects on water availability and crop yields depending on geographical location. On a balance, climate change can limit global water availability and food production while increasing water consumption in all economic sectors (Strzepek and Boehlert, 2010; DaMatta et al., 2010). Land use and population change will also have direct and indirect effects on global food and water demand and supply (Huang et al., 2010; Thomson et al., 2013; Foresight, 2011). Because crop yields and water use efficiency cannot be increased infinitely, total land area allocated to crop production would be a major determinant of future food availability even in environments where climate change could be beneficial (Yawson et al., 2017). Based on population projections, global food demand will rise sharply up to the 2050s (Spring, 2009). Global meat demand, for example, is projected to reach 49 kg per person by 2050, with demand in high income countries approximating 91 kg per person (Alexandratos and Bruinsma, 2012). This will require a global supply of about 455 million tons of total meat and about 1.1 billion tons of animal feed (Alexandratos and Bruinsma, 2012; De Fraiture et al., 2007). This demand for meat, and for that matter animal feed, will have a cascading effect on grain production and consumption as feed use accounts for a larger proportion of grains produced worldwide. To meet food production needs in the 2050s, it is estimated that additional 5,600 (De Fraiture et al., 2007) to 5800 $km^3 yr^{-1}$ (Rockström et al., 2009) of water over current levels will have to be mobilized. In the context of these projections, virtual water could play a more significant role in water-food security policies and strategies in the future.

However, while there is considerable volume of literature on virtual water under current conditions, research on the flows and utility of virtual water for water-food security under projected climate, land use, and population changes is very limited. Konar et al. (2013) studied global virtual water flows and savings under climate change (using the SRES A2 scenario) in the 2030s. They employed the GTAP trade model to obtain future bilateral trade flows and the H08 hydrological model to obtain future crop evapotranspiration. Future crop yields were obtained from expert projections and were combined with the crop evapotranspiration to obtain future virtual water content of soy, rice, and wheat. The results from the two models were combined to obtain future virtual water flows and savings. They reported that the total volume of virtual water flows will likely decrease under climate change in the 2030s due to a dampening effect of higher prices under low yield scenario, and higher crop water productivity under high yield scenarios. They indicated the need for more studies in this area, noting the difficulty and the imperative of integrating more factors in a single analytical framework. Other studies have considered the interactive effect of trade and climate change on agriculture (Calzadilla et al., 2011), or blue water scarcity and the economic impacts of future agricultural trade (Schmitz et al., 2013). Certainly, there is scope for assessing the combined effect of climate, land use, and population changes on future virtual water flows to contribute to adaptive policy decisions.

The current study uses the UK and feed barley (and its associated meat production) as a case study to estimate future virtual water flows and the associated environmental and food security implications for the UK. Barley (*Hordeum vulgare* L.) is a coarse grain crop that plays crucial roles in global food security. In terms of quantity produced, it is the fourth most important cereal crop that feeds the world (Newton et al., 2011). Feed use accounts for about 53% of global barley production, with the remaining going into industrial uses (such as malting) and others (Newton et al., 2011). Barley is the largest component of coarse grains used as animal feed worldwide (Newton et al., 2011). In the UK, barley is the second most important arable crop and the number one crop in Scotland, and wheat and barley account for about 50% of UK cultivated land (Defra, 2011). Feed use accounts for over 60% of total barley produced in the UK, and barley accounts for about 39% of total feed use of grains (Defra, 2011). In the UK and the EU, about 52% and 54%, respectively, of total grains produced are used as animal feed (Foresight, 2011; Bruinsma, 2012).

Currently, the UK has a high rate of self-sufficiency in barley production but has trade deficit in meat and aggregate feed (Defra, 2011). While climate change could be beneficial to UK barley production (Yawson et al., 2016), the UK could face substantial deficit in feed barley supply from domestic production, with adverse implications for meat production (Yawson et al., 2017). This deficit could be offset through import of either feed barley or feed barley equivalent meat, resulting in virtual water flows to the UK and potential impacts on the water resources of exporting countries. This paper therefore assessed the future virtual water flows of the UK under the combined effect of climate, land use, and population change on aggregate demand and supply of feed barley and, consequently meat, from the 2030s to the 2050s. The paper aims to highlight the future utility of virtual water in supporting strategic and adaptive food trade decisions that address water and food security needs in response to climate, land use and population changes.

2. Methods

2.1. Baseline metrics

The Food Balance Sheet (FBS), published by the Food and Agriculture Organization (FAO) of the United Nations, is useful for estimating shortages or surpluses of food, projecting future food needs and making policies regarding food production and trade (Kearney, 2010). It captures the supply and utilization of food items in a given country over a reference period which is a 3-year average. Total supply of a given food item in the FBS refers to the total quantity of domestic production plus imports, adjusted for changes in stocks that might have occurred since the beginning of the reference period. On the utilization side, the total supply is distributed over quantities exported, used as animal feed and seed, processed for food and non-food uses, losses during transportation and the proportion available for human consumption. In the current study, baseline metrics on feed barley and meat supply and usage were derived from the UK FBS (FAOSTAT, 2009). With barley, feed use of barley was calculated as a proportion of total quantity available for domestic use. This, and the proportionate feed barley in total feed grain, were considered representative and assumed to remain unchanged for the calculation of future feed barley supply from total production. In this study, total meat refers to the sum of bovine, mutton and goat, 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. The FBEM is 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). This enabled the derivation of a constant that relates unit feed barley consumption to meat production in the future. More details of the methods used here can be found in Yawson (2013).

2.2. The future situation

Daily climate variables for the 2030s, 2040s and 2050s were obtained for three emissions scenarios (high, medium, and low; hereafter HES, MES, and LES, respectively) from the UKCP09 (Murphy et al., 2009) using the embedded weather generator (Jones et al., 2009). The soil data was obtained from the Crop Growth Monitoring System (CGMS) database in the New Soil Information System (SINFO), which is part of the European Union programme on Monitoring Agriculture with Remote Sensing (MARS) Crop Yield Forecasting System (Baruth et al., 2006). The climate data, together with crop (based on the barley genotype Westminster) and soil data, were used to simulate barley grain yields and crop evapotranspiration in the 2030s, 2040s, and 2050s using AquaCrop (Raes et al., 2009) calibrated and validated under Scottish conditions (i.e. the relevant datasets for the calibration and validation were collected from barley genotypes grown in the field in Scotland). The climate change simulation was done for the fourteen UK administrative regions and the results were aggregated to the UK national level (see Yawson, 2013). The effect of climate change on UK barley yields has been reported in Yawson et al. (2016). With land use, a business as usual land use scenario (BAU) was represented by the average land area under barley cultivation for the period 2000–2012. Projected areas of croplands in the UK for the three time slices were taken from the study by Thomson et al. (2013) on future land use states and greenhouse gas emissions or removals in the UK. Thomson et al. (2013) used four land use scenarios (business as usual, high, low, and mid). The total areas of cropland under the mid scenario were used for the current study. The mid scenario is mid-way between the high scenario (which emphasizes expansion in food production with little emphasis on bio-energy crops and forestry) and the low scenario (which emphasizes expansion in production of bio-energy crops and woodland). The average of total area of land under barley cultivation for the period 2000–2012 as a proportion of average total area of cropland for the same time period was calculated and this proportion was assumed to remain unchanged to the 2050s. The area of land under barley cultivation for this period was used to represent a 'business as usual' (BAU) scenario. This proportion was then applied to the projected cropland areas obtained from Thomson et al. (2013) to generate future area of land under barley for the three time slices. Additional future land use states (Mid±20% at 5% intervals) were created based on the calculated land area under barley and the range of observed rates of barley land use change for the period 2000–2012 to account for crop-specific land use changes in response to market and/or other non-policy signals which were not accounted for by Thomson et al. (2013). Total barley production was obtained as the product of the mean barley grain yield and the projected total land area for barley for each time slice and emissions scenario.

The UK population for the 2030s, 2040s and 2050s were obtained from the UK National Population Projections (2010–2085) datasets by the Office of National Statistics. This dataset has four scenarios: high fertility, low fertility, constant fertility, and balanced long-term migration. However, the constant fertility scenario was used as a basis for calculating the deficits in feed barley and meat supply, and therefore the associated virtual water flows. Future per capita demand for meat and feed grain was obtained from the Comprehensive Assessment of Water Management in Agriculture (2007) report. The proportional contribution of feed barley to feed grain demand was calculated, and subsequently, feed barley equivalent meat demand. Finally, total feed barley or feed barley equivalent meat demand was calculated by multiplying the future population by the per capita feed barley demand or the meat demand, respectively. The deficit in supply was obtained as the difference between the projected demand and domestic supply of feed barley or meat. A graphical overview of the approach adopted is shown in Figure 1.

The current paper focuses on virtual water flows associated with imports to balance deficits in feed barley and meat supply. The virtual water content (VWC, m^3 ton^{-1}) of future UK barley production was calculated using Eq. (1):

$$\boldsymbol{VWC} = 10.\frac{\boldsymbol{ETc}}{\boldsymbol{Yield}} \qquad \text{Equation 1}$$

where *ETc* is the total crop water use (mm); and 10 is a scalar to ensure consistent units (Chatterton et al., 2010). The ETc and yield values were obtained from the climate change simulations. For each emissions scenario and time slice, the mean ETc and barley grain yield for the UK was used. Total virtual water (TVW, m^3) of barley was estimated using Eq. (2) below:

$$\boldsymbol{TVW} = \boldsymbol{VWC.T} \qquad \text{Equation 2}$$

where T is the total food item (tons) considered.

In this study, it was assumed that the UK would import feed barley or meat to offset deficits from domestic production. So, the virtual water flows associated with these imports were calculated. The UK imports of barley and meat for the baseline period were obtained from the FAOSTAT trade database. With regard to barley, eight out of twenty one countries accounted for about 95% of total UK imports. The remaining countries contributed less than 2% each to the total import, so they were aggregated as the 'rest of the world'. It was assumed that these countries would remain as sources of UK barley import to the 2050s. For each exporting country, the average VWC of barley was retrieved from the WaterStat Database of the Water Footprint Network (www.waterfootprint.org) (Mekonnen and Hoekstra, 2010a). Total virtual water flows were then calculated using Eq. (2).

With meat, 10 countries (out of 49) contributed 92% of total meat import to the UK. The remaining countries accounted for less than 2% each and were aggregated as 'the rest of the world'. Based on the same assumption as for the barley, the VWC of meat for the exporting countries were retrieved from the WaterStat Database of the Water Footprint Network (Mekonnen and Hoekstra, 2010b). Here, the weighted averages of the VWC of fresh or chilled carcasses of bovine, lamb and goat, pork and poultry were retrieved and averaged to represent the VWC of total meat for each country. This was done because the weighted average of VWC of products in this database comprises a mix of production systems (grazing, mixed, and industrial). The average (including the world average) of the VWC of total meat for all countries was used to calculate the virtual water flows of meat import using Eq. (2). However, the blue and green VWC were calculated separately. To account for potential changes in water use due to climate change (e.g. water for cooling or to avoid heat stress), the blue VWC of meat in the partner countries was adjusted upward by 2.5% while green VWC of barley in the partner countries was adjusted downwards by 10%. This magnitude of reduction in the green VWC was based on average gains in water productivity across the fourteen UK regions from the low to high emissions scenarios and from the 2030s to the 2050s (see Figure 2). Because most of the partner countries for barley trade were in northern temperate environment, it was assumed that on a balance, there would be net water productivity gain equivalent to the mean of productivity gains across the fourteen UK regions. Conversely, the magnitude of the upward review of the blue VWC in partner countries (which were largely temperate countries) was discretionary, but based on the expected increase in water

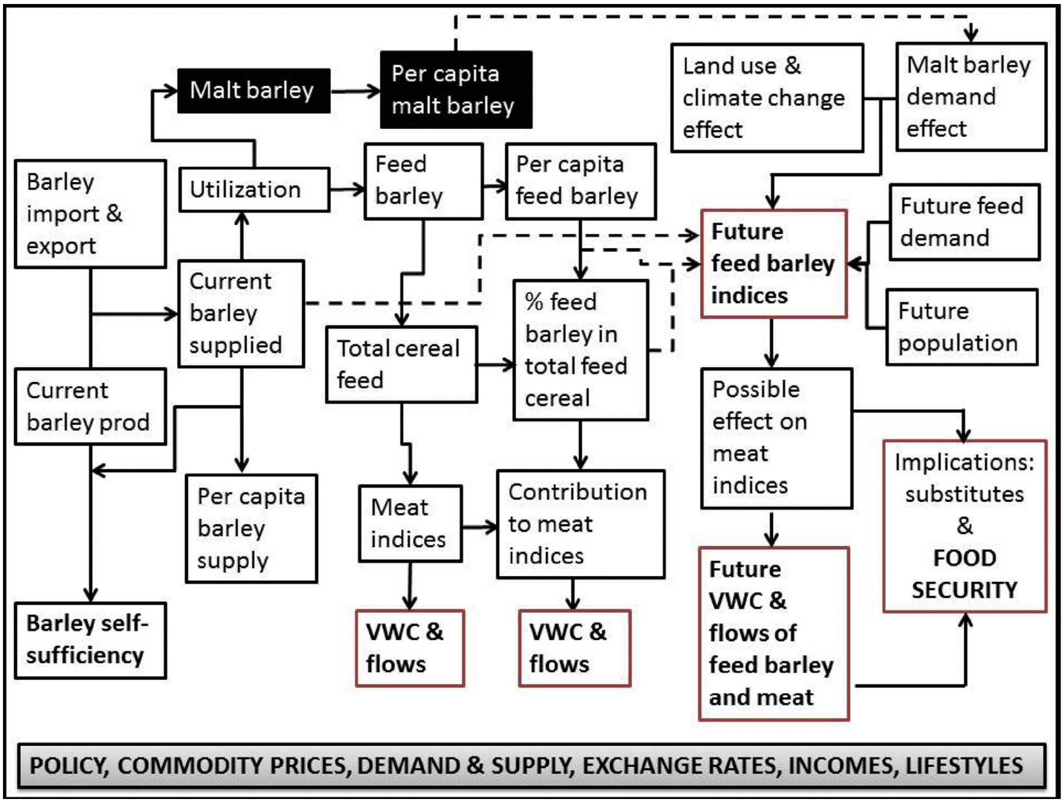

Figure 1. Graphical presentation of the approach adopted in the current study.

requirement of farm animals, especially for cooling during summer (Flamenbaum and Galon, 2010; Lee, 1993). This was based on further assumption that productivity gains from climate change in northern temperate countries could compensate for decreases in other countries. Grey water was not considered in the current study.

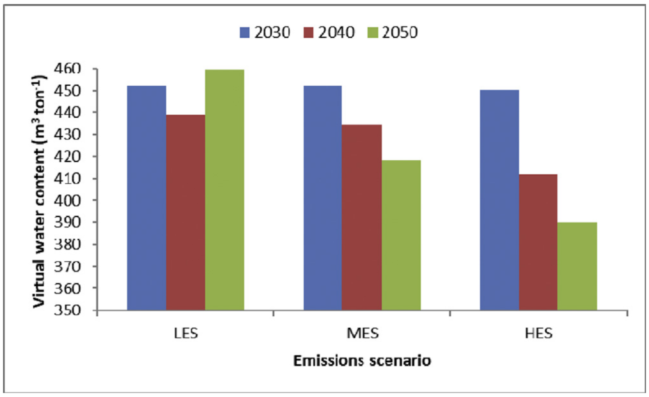

Figure 2. Virtual water content of UK barley grain under the LES, MES, and HES in the 2030s, 2040s, and 2050s.

3. Results

3.1. Projected feed barley and meat demand

Using the constant fertility scenario, UK population is projected to be 71.9, 76.1 and 80.3 million for the 2030s, 2040s and 2050s, respectively (Table 1). The corresponding total meat demand values were 6,902, 7,344 and 7,789 thousand tons respectively, while total feed grain demand values were 28,472, 30,212 and 31, 959 thousand tons respectively (data not shown). 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 the 2030s, 2040s, and 2050s. For the same time slices, the feed barley equivalent meat demand was 2,657, 2,827 and 2,999 thousand tons, respectively.

The effect of climate change on the barley yields has been reported in Yawson et al. (2016). The large demand compared to total production resulted in large deficits in feed barley supply from domestic production even if total barley produced in the UK is used as feed (Table 2). The largest deficits would be under the LES due to lower yields compared to the HES, and under the Mid-20% land use scenario. Assuming land use remains unchanged (BAU), the deficit in feed barley supply (if total barley produced is used as feed) would range from 4,262 (HES, 2030) to 5,697 thousand tons (LES, 2050). Considerable reduction in this deficit is

Table 1. Projected UK population, total feed barley and feed barley equivalent meat demand.

Fertility scenario	Total population (million)			Total feed barley demand ('000 tons)			Total feed barley equivalent meat demand ('000 tons)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
High	72.8	77.3	82.2	11,099	11,815	12,596	2,691	2,872	3,070
Constant	71.9	76.1	80.3	10,962	11,632	12,304	2,657	2,827	2,999
Low	69.5	72.0	74.0	10,596	11,005	11,339	2,569	2,675	2,764
Balanced long-term migration	70.3	71.5	71.9	10,718	10,928	11,017	2,598	2,656	2,685

Table 2. Projected deficits (‘000 tons) in UK total feed barley if total barley produced domestically is used as feed (under the constant population growth scenario).

Land use scenario	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	4,765	4,334	4,262	5,230	4,758	4,306	5,697	4,876	4,332
Mid	5,254	4,857	4,791	5,679	5,240	4,820	6,102	5,332	4,821
Mid+5	4,969	4,552	4,483	5,381	4,921	4,480	5,792	4,983	4,447
Mid+10	4,683	4,247	4,174	5,084	4,601	4,139	5,482	4,635	4,073
Mid+15	4,398	3,942	3,866	4,786	4,281	3,799	5,172	4,286	3,699
Mid+20	4,113	3,636	3,557	4,488	3,962	3,458	4,862	3,937	3,325
Mid-5	5,540	5,163	5,100	5,977	5,560	5,161	6,412	5,680	5,196
Mid-10	5,825	5,468	5,408	6,274	5,879	5,502	6,722	6,029	5,570
Mid-15	6,110	5,773	5,717	6,572	6,199	5,842	7,033	6,378	5,944
Mid-20	6,396	6,078	6,025	6,870	6,519	6,183	7,343	6,726	6,318

seen from the Mid+15% scenario, implying that total land area committed to barley production would have to increase by at least 15% over current level before a substantial decrease in feed barley deficit can be realized.

3.2. Projected virtual water flows

3.2.1. Virtual water content of UK barley

The virtual water content of UK barley production for the three emissions scenarios and time slices are shown in Figure 2. The virtual water content of barley decreased from the 2030s to the 2050s, except under the LES where the virtual water content was highest in the 2050s. Between the emissions scenarios, the virtual water content did not differ substantially in the 2030s. Substantial variations are, however, observable in the 2050s.

Total virtual water associated with total UK barley production ranged from 206 (Mid-20, LES) in the 2030s to 350 million m^3 (Mid+20, HES/MES) in the 2050s (Table 3). Without land use change effect (BAU), total virtual water ranged from 280 million to 311 million m^3 in the 2030s and 2050s, respectively. Under the Mid scenario, total virtual water associated with barley production ranged from 258 million in the 2030s to 292 million m^3 in the 2050s. The wider range of total virtual water associated with only feed barley supply from domestic production was 105 (LES, Mid-20) in the 2030s to 178 million m^3 (MES/HES, Mid+20) in the 2050s (Table 4). The range under the BAU was 143–158 million m^3, while the range under the Mid scenario was 131–148 million m^3, in the 2030s and 2050s, respectively. The least and largest total virtual water associated with UK barley production occurred under the LES and Mid-20 in the 2030s and the MES/HES and Mid+20 in the 2050s. It must be noted that this virtual water is entirely green as the simulation was done under rainfed conditions.

The mean green and blue virtual water content of imported barley was 737 and 21 m^3 ton^{-1}, respectively. Assuming total barley produced in the UK is used for animal feed, the least and largest total virtual water associated with barley import to balance the deficit would range from 2.5 to 5.6 billion m^3 under the Mid+20 (HES) and Mid-20 (LES), respectively in the 2050s (Figure 3). Generally, the virtual water flows increase across the time slices for all emissions scenarios. However, a reversal in this trend begins to occur for HES from the Mid+5 scenario where a marginal increase across the time slices is observed due to relatively higher yields. The virtual water flows associated with barley import under both the Mid and Mid+5 exceed that of the BAU, indicating greater imports under the former land use scenarios. On the other hand, if total barley produced is distributed to different end uses as it is currently, the virtual water inflows associated with imports to balance deficit from domestic supply of feed barley will increase by more than 2 billion m^3 (Figure 4). In this case, the total virtual water inflows could be as high as 7.4 billion m^3 in the 2050s; and the virtual water inflows under the LES and MES would not differ substantially in the 2040s and 2050s. Green water accounted for 97% of the total virtual water inflows.

The average green and blue virtual water content of total meat were 3,905 and 243 m^3 ton^{-1}, respectively. If the UK were to import meat (instead of feed barley) to balance the deficit in barley equivalent meat, the virtual water inflows to the UK (Figure 5) would be larger than those for feed barley import. Deficit arising from use of total barley produced as feed would result in virtual water inflows ranging from 3.3 to 7.4 billion m^3. Here, the virtual water inflows will increase across the three time slices for all emissions scenarios but will be largest under the LES. For the BAU scenario, total virtual water inflows will range from about 4.3 to 5.8 billion m^3, and these will be lower than or quite close to the corresponding values under the Mid, Mid+5, and Mid+10 scenarios.

The virtual water associated with meat import in response to deficit arising from domestically available feed barley is presented in Figure 6. In this case, the virtual water inflows to the UK increase further, with the highest being about 9.9 billion m^3 under the LES and Mid-20 scenario in the 2050s. The virtual water inflows associated with meat import under

Table 3. Projected total virtual water (‘x10^6 m^3) associated with total barley production in the UK.

Land use scenario	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	280	300	302	281	299	302	304	311	311
Mid	258	276	278	261	278	280	285	292	292
Mid+5	271	290	292	274	291	294	299	306	306
Mid+10	284	304	306	288	305	309	314	321	321
Mid+15	297	317	319	301	319	323	328	336	336
Mid+20	310	331	333	314	333	337	342	350	350
Mid-5	245	262	264	248	264	266	271	277	277
Mid-10	232	248	250	235	250	252	257	263	263
Mid-15	219	235	236	222	236	238	242	248	248
Mid-20	206	221	222	209	222	224	228	233	233

Table 4. Projected total virtual water ('x 10^6 m^3) associated with proportionate domestic feed barley supply.

Land use scenario	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	143	152	153	143	152	153	155	158	158
Mid	131	140	141	133	141	143	145	148	148
Mid+5	138	147	148	140	148	150	152	156	156
Mid+10	144	154	155	146	155	157	160	163	163
Mid+15	151	161	163	153	162	164	167	171	171
Mid+20	158	168	170	160	169	171	174	178	178
Mid-5	125	133	134	126	134	136	138	141	141
Mid-10	118	126	127	120	127	128	131	134	134
Mid-15	112	119	120	113	120	121	123	126	126
Mid-20	105	112	113	106	113	114	116	119	119

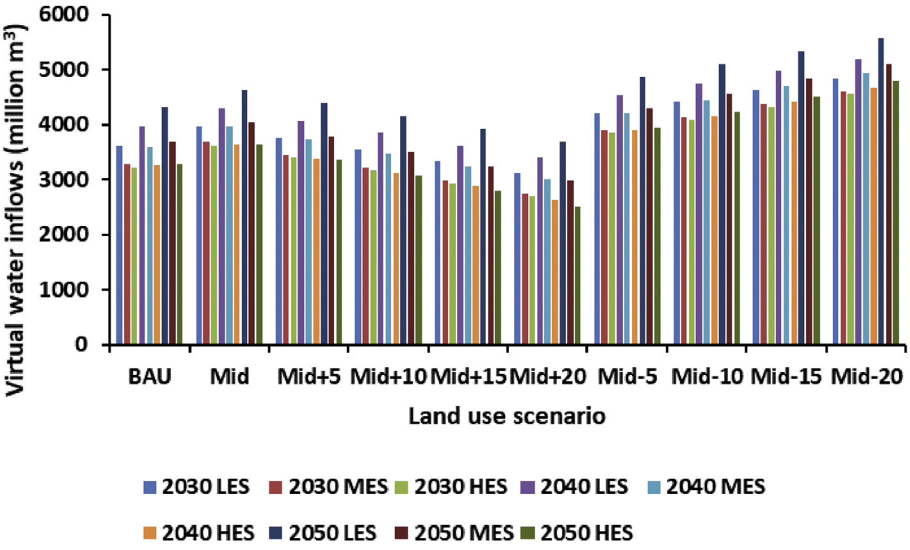

Figure 3. Total virtual water inflows (million m^3) due to import of barley to balance deficit from total production. Note: green water = 97%.

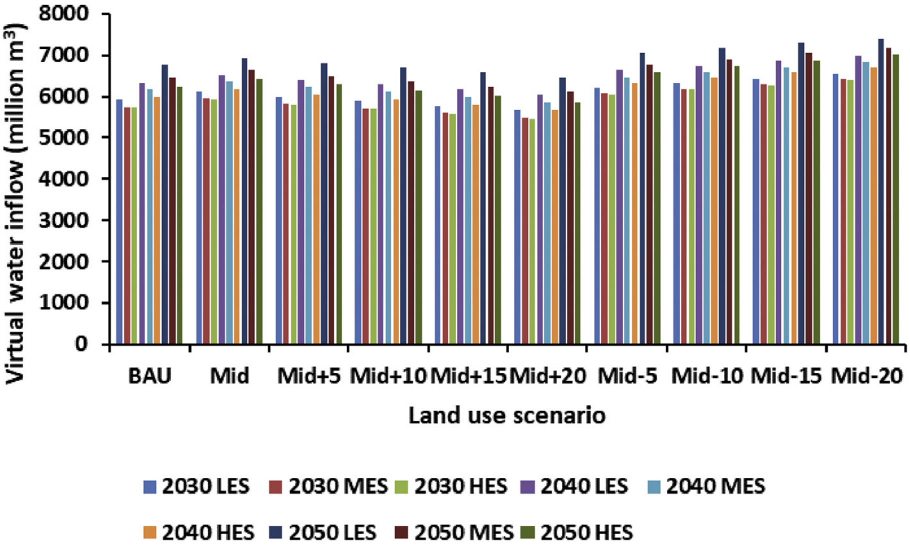

Figure 4. Total virtual water inflows (million m^3) to the UK due to feed barley import to balance deficit from domestic supply. Note: Green water = 97%.

the BAU will be larger than the maximum virtual water inflow associated with the Mid-20 scenario when total barley produced is used for feed. Here, the virtual water inflows under the HES for most of the land use scenarios do not differ substantially in the 2050s, indicating the inability of the relatively higher yields of barley under the HES to substantially reduce virtual water inflows. Green water accounted for 94% of the

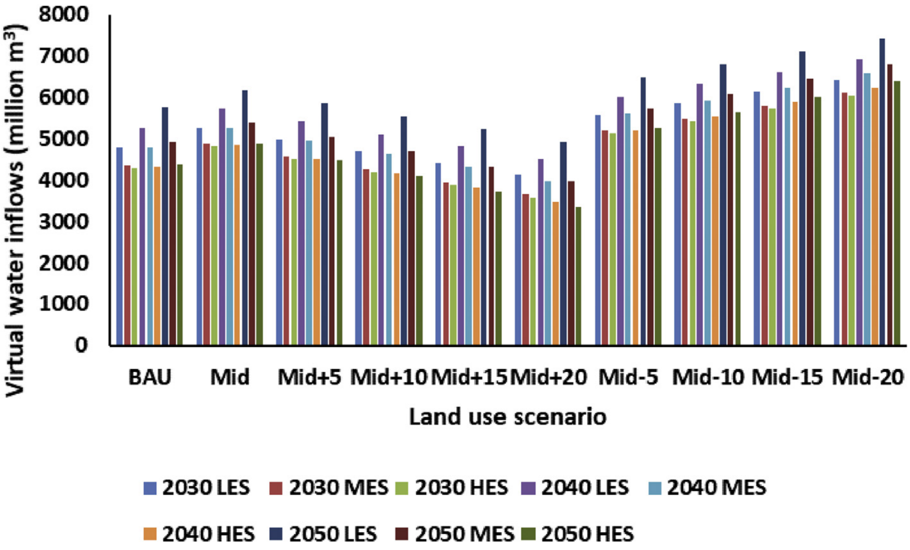

Figure 5. Virtual water inflows (million m^3) associated with total meat import to offset deficit from total barley production. Note: Green water = 94%.

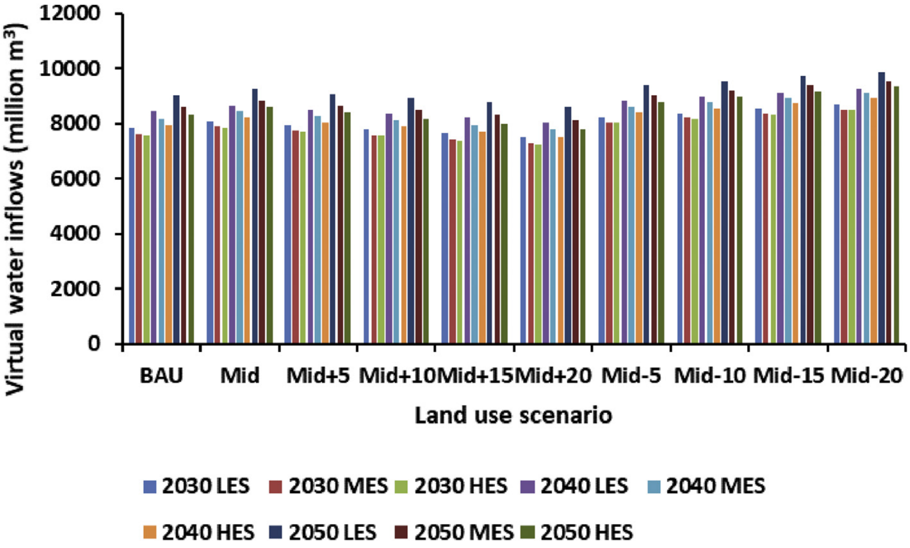

Figure 6. Virtual water inflows (million m^3) to the UK due to total meat import to balance deficit in feed barley equivalent meat from domestic feed barley supply. Note: Green water = 94%.

virtual water inflow associated with meat import while blue water accounted for 6%.

4. Discussion

The virtual water concept has revealed the potential to address water and food security needs by using resources circulated through food commodity trade (Allan, 1998; Hoekstra, 2010; Yawson et al., 2013; 2014). Estimates of future virtual water flows under projected climate, land use, and population changes can inform adaptive and strategic trade decisions. The current study estimated future virtual water flows of the UK under the combined effect of climate, land use (in response to climate mitigation policies), and population change on demand and supply of feed barley and meat, from the 2030s to the 2050s. Barley is used because of its multiple uses, direct and indirect effect on food security, and its adaptability to a wide range of environments. Moreover, meat contributes substantial proportion of daily calories in the UK diets. Meat and other animal products (mainly dairy) are a rich source of high value protein and essential micronutrients such as vitamin A, iron and zinc. Hence, adequate supply of barley as a major source of animal feed, or meat is important for UK food security (Foresight, 2011).

Currently, the UK has a high self-sufficiency rate in barley production and almost all its feed barley is supplied from domestic production (Defra, 2011). Barley yields in the UK are projected to increase, or barley production would remain viable under projected climate change (Yawson et al., 2016). It is noted, however, that the UK would face huge deficits in feed barley supply in the future, driven mainly by the respective effects of population growth on demand and land use limitations on supply due to climate mitigation efforts (Tables 1 and 2; Yawson et al., 2017). The study assumed that the UK would import feed barley or the equivalent of meat that could be produced with the barley in any given feed mix.

The virtual water content of UK barley would decrease from the 2030s to the 2050s, especially under the MES and HES scenarios (Figure 2). This is due to increased yields and water use efficiency, especially under the MES and HES (Yawson et al., 2016). This implies that the volume of virtual water associated with barley production in the UK would be increasing at a decreasing rate across the time slices, especially under the MES and HES; but the observed magnitude of increase in the volume of virtual water will be due to the marginal increase in land allocated to barley production. Konar et al. (2013) observed that total global virtual water flows associated with wheat, rice and soy in 2030 could decrease due to enhanced crop productivity under high yield scenario. The result in the current study suggests that the UK could contribute to global water savings if it were to have surplus barley for export.

Import of barley to balance the domestic deficits would result in large virtual water flows to the UK, far in excess of virtual water associated with UK domestic production. Total virtual water associated with total UK barley production from the 2030s to the 2050s under all land use and emissions scenarios ranged from 206 to 350 million m^3. The corresponding values for barley import to offset deficits arising from feed use of total barley production were 2.5–5.6 billion m^3. On the other hand, if barley produced in the UK were distributed to the various end uses, the virtual water associated with imports of barley to balance deficits due to domestic feed barley supply would be as high as 7.4 billion m^3. This large difference suggests that even if productivity gains in exporting countries were equivalent to gains in the UK, there would still be large virtual water flows to the UK due to increased demand and land use constraints to production or supply. Similarly, virtual water associated with imports of feed barley equivalent meat would range from 3.3 to 7.4 billion m^3 (if total barley produced were used as feed), or as high as 9.9 billion m^3 (if barley produced domestically were distributed to different end uses). Clearly, within the limits of the current study, considerable virtual water inflows to the UK can be expected due to imports of barley or meat, from the 2030s to the 2050s under all climate, land use and population change scenarios.

The main sources of barley import to the UK were Ireland (44%), France (16.4%), Germany (12.6%), Ukraine (6.8%), Spain (5.1%), Denmark (3.8%), Sweden (3.6%), and Italy (2.6%). The top meat export sources were Ireland (20.4%), Netherlands (20.9%), Denmark (14.7%), Germany (8.2%), New Zealand (8.2%), Belgium (6.1%), France (6.1%), Spain (2.7%), Poland (2.6%), and Brazil (2.1%). While total UK barley production in the future would be 100% green water, blue water would account for 3% and 6%, respectively, for barley and meat imports to the UK. For example, blue water associated with imports of feed barley equivalent meat would range from 440 million m^3 in the 2030s to 579 million m^3 in the 2050s (data not shown), which are in excess of total virtual water associated with total UK barley production. The inflows of blue water to the UK has environmental and socio-economic implications (Aldaya et al., 2010; Hoff et al., 2010; Chapagain and Orr, 2009) that require further investigation to determine potential impacts depending on the geographic location of water withdrawal and water stresses associated with that area.

Few studies have estimated virtual water flows under projected climate change. To our knowledge, the current study is the first attempt to estimate virtual water flows under the combined influence of climate, land use (in response to land-based climate mitigation policies), and population change. Konar et al. (2013) estimated global virtual water flows associated with rice, soy and wheat in 2030 using one emission scenario. Their study was based on price elasticities of the commodities at a global scale and at one time step. The current study was based on aggregate demand and supply at national level (mediated by climate, land use, and population growth) across three time slices and emissions scenarios to permit a more nuanced understanding of the impact of national production on food security needs and trade flows. For example, while Konar et al. (2013) reported that crop productivity gains would dampen total virtual water flows in 2030, the results of the current study suggest that productivity gains in the UK would not be sufficient to substantially reduce virtual water inflows due to the large deficits that would be incurred.

By linking water and food through trade, virtual water globalizes the concerns in the nexus of water and food security and provides an avenue for examining the global trade architecture and institutional framework for water resources governance and management. It is this prospect which has attracted much attention to virtual water as a potential policy and global governance tool for water-food security (Hoekstra, 2010). The results in the current study raises two issues that should be of interest to future global water-food security. Firstly, climate beneficiary countries, such as the UK, should strive to produce surplus barley for export to less water-efficient countries if future global water savings are to occur and not the other way around. Secondly, effort to maintain surplus under water-efficient and high-yield conditions is imperative to ease the prospect of intense competition for feed barley or meat in future global markets and its implications for economically poor, and water-inefficient countries. Even though developing countries are projected to present a strong competitive demand for feed and meat (Bruinsma, 2012; Alexandratos and Bruinsma, 2012), their economic and technical capacities are relatively lower than the climate beneficiary countries. This imbalance ought to be of interest or value to the discourse on water-food security responses to global environmental change.

It has been suggested that, for virtual water savings to occur, the net virtual water flow (difference between imported and exported virtual water) should be positive and the water productivity or availability in the importing nation should be lower than that of the exporting nation (e.g. Yang et al., 2006). Based on this, the future virtual water flows to the UK would not contribute to global water savings, since the net virtual water flow would be negative and there would be blue water flows to a 100% green water production country. Yawson et al. (2013) suggested the agri-compatibility framework for assessing the utility or the instrumental value of virtual water for addressing water and food security concerns concurrently. Meaning, food commodity import ought to serve the twin imperatives of water-scarcity and food security needs (‘water-dependent food security’ needs) without adverse impacts in the exporting country. Thus, water-limited food production should explicitly drive food import to serve food security needs. Once this is established, the practical value of the magnitude of water savings becomes immediately visible; and herein lies the instrumentality of virtual water for addressing concurrently the future water and food security goals or needs. In the current study, it can be said that the virtual water flows to the UK is not agri-compatible since the imports are not necessitated by water-limited production. Rather, the imports are necessitated by increase in demand due to population growth and land use constraints to production. Indeed, population growth will principally account for increases in meat demand in high income countries such as the UK (Alexandratos and Bruinsma, 2012; Thornton, 2010; De Fraiture et al., 2007). In addition, import of meat and animal feed to Europe is projected to rise substantially in the future, perhaps due to increasing focus on bioenergy to achieve renewable energy targets (Bruinsma, 2012; European Commission, 2011). Here, the imports would be driven primarily by food security imperatives and not by interest in national or global water savings. From the current study, it is important for the UK to take measures to shift potential imports from blue water sources, especially in Spain and Southern France where water scarcity issues can exist. It is also important for the UK to carefully consider land use futures that do not considerably reduce food production while managing both population growth and food demand.

5. Assumptions and limitations

Projections are based on a set of assumptions. In the current study, several assumptions were made that limits the study and provides scope for refinements in future studies. Firstly, the proportion of feed barley supply from total domestic production was assumed to remain unchanged to the 2050s. Of course, the results obtained would be at variance with a situation in which the proportions vary over time due to changing production and socio-economic circumstances (which is a more realistic expectation but difficult to estimate). Secondly, the feed grain requirements and use efficiencies are different for different animals (Pollock, 2011; Thornton, 2010). For example, beef cattle require about five times the dietary energy of poultry. As a result, the actual total feed barley demand in the future will also depend on the proportions of different types of meat that will be demanded or produced. Thirdly, the main export partners of the UK were assumed to remain unchanged to the 2050s. Future trade partners and volumes of trade will be dictated by production conditions as well as political circumstances. For example, the Brexit (Britain exiting the EU) could alter the trade partners and patterns for the UK. Fourthly, even though the genotype Westminster is grown both as winter and spring barley, the climate change simulation in the current study was done under spring growing conditions as this is better for assessment of the effect of water deficit and heat stress on barley yields. Winter barley, which is considerably used for animal feed, has higher yield but lower total production and land area compared to spring barley. However, the proportion of feed use of barley used in the current study was based on total barley production (both winter and spring). Hence, the relatively higher yield of winter barley could be compensated for by the larger land area (and for that matter the larger production) of spring barley. This notwithstanding, the current study could overestimate future feed barley availability from domestic production and therefore underestimate the virtual water inflows. Finally, the virtual water content of barley or meat in the export countries could vary from those used in the current study due to changes in productivity gains resulting from ecological change and agronomic management practices. It was assumed that the exporting countries would remain as the UK trading partners and maintain production potential to the 2050s. This might vary in response to environmental, socio-economic and political circumstances.

6. Conclusions

Projected climate, land use and population changes have serious implications for food demand and supply, and therefore food commodity trade in the future. Virtual water captures the flow of productive water resources through food commodity trade. The current study is a first attempt to quantify future virtual water flows under the combined influence of climate, land use, and population changes over three time slices and three emissions scenarios using the UK and feed barley as a case. For the UK, population and land use changes would combine to create large deficits in feed barley or meat supply, resulting in large inflows of virtual water from imports. The total volume of virtual water inflows for all land use scenarios, emissions scenarios, and time slices under the constant population scenario were larger than the total volume of virtual water associated with domestic barley production in the UK. Imports of meat would result in even larger virtual water inflows. The virtual water inflows to the UK would not be agri-compatible and would not constitute global water savings. While UK barley production would be entirely green, blue water would account for 3% of UK virtual water inflows in the future. The large blue water inflows associated with barley and meat import suggests the need for the UK to shift potential imports from especially locations that could have water stresses. The results in the current study can be an input to the UK's future trade policy and strategy to assure food security while minimizing environmental impacts in exporting countries. Especially, with Brexit on the horizon, the UK needs to make strategic efforts to diversify its trading partners to ensure sustainable imports. It is also imperative for potential climate beneficiaries such as the UK to strive to maintain, at least, adequate production of feed barley to contribute to global water savings and ease anticipated pressure on future food markets which could adversely affect poor and water-inefficient economies.

Declarations

Author contribution statement

DO Yawson: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

S Mohan, T Ball, B Mulholland, PJ White: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

FA Armah, MO Adu: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

The sources of all publicly available data used are provided in the manuscript. However, the resulting data used in this paper are available in the thesis at https://discovery.dundee.ac.uk/en/studentTheses/climate-change-and-virtualwater, or available upon request.

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