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Embodied water imports to the UK under climate change

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ABSTRACT: Commodities such as food and manufactured goods, particularly those that rely on land and water, are increasingly recognised as being potentially sensitive to climate change on a global scale, suggesting that the international dimension is critical when considering future supply susceptibilities of import-dependent countries, such as the UK. We estimated embodied water imported to the UK for 25 economically significant and climate-sensitive sub-sectors, then explored the current and future susceptibilities of these sub-sectors under climate change. In 2010, these products represented 31% of total UK imports by value (US$) and 12.8 billion m^3 of embodied water. Of this total, rice, bovine and pig meat production, plastics and paper account for ~60% of the volume of water embodied in the import categories considered. By combining product-based water volume estimates with economic and climate model information, we show how the UK could be increasingly susceptible to loss of these water supplements in the future. In doing so, we provide an indication of how countries that depend upon climate-sensitive imported resources can account for these dependencies in a systematic way. For example, international adaptation and development funding may be targeted to the securing of supplies from existing exporting countries, or trade relations may be encouraged with potential new suppliers who are likely to be less resource-constrained.

KEY WORDS: Climate risks · Import · Virtual water trade

1. INTRODUCTION

A growing number of countries have undertaken formal climate change analyses focussing on risks directly occurring in the country itself (e.g. DEFRA 2012). However, fewer studies have appraised risks to countries and their citizens that originate from the international dimensions of climate change. It is now recognised that more detailed, and quantitative, analysis is needed to understand the relative importance of both direct domestic risks and indirect international climate risks to the UK—in particular, those risks in the latter group that may affect the security of food supplies and other essential commodities—and the implications for associated national policies.

This study contributes evidence of international risks by examining the relationship between projected water resource susceptibilities in the UK and its trade partners under climate change and the potential resulting effects on patterns of trade. Our chosen metric is the amount of water embodied in the production of primary and manufactured goods that are subsequently exported to the UK. The concept (also known as the 'virtual water' trade) was first introduced as a hydro-political solution to potential regional conflicts over water scarcity (Allan 1993). Contrary to public perceptions of resource abundance, it is now known that in aggregate, the UK is currently a net importer of water (e.g. Chapagain & Hoekstra 2008, Chapagain & Orr 2008, Milà i Canals et al. 2010, Yu et al. 2010).

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In fact, it is estimated that ~70% of the total water used in production and consumption in the UK (73 billion m^3 yr^{-1}) is imported from other countries in the form of water embodied in goods (Chapagain & Hoekstra 2008). As such, the UK is one of the most water import-dependent nations in the world, alongside a small number of other North European countries and Middle Eastern states. This is a striking statistic, given that imports equate to just 15% of the UK economy by value (ONS 2011). The water use per unit of production in the UK is higher than many of the countries that currently export to the UK. Moreover, the UK is not able to substitute all foreign imports for domestic production, so the role of international trade and implied access to water is essential to maintaining current patterns of consumption.

Viewed another way, the total water volume needed to produce the goods and services consumed by the UK population, including the water embodied in imports, is 51% of the total national renewable water resource available (estimated to be 147 billion m^3 yr^{-1}) (Chapagain & Hoekstra 2008). However, in parts of southeast England, actual and licensed water withdrawals from the environment already exceed sustainable levels (EA 2009). Furthermore, pressures on UK water resources are projected to increase in the future, as a result of population growth (an expected 12% increase over the next 20 yr [ONS 2010]), economic growth and climate change (ASC 2012). Hence, the net flow in embodied water will also be an important, indirect determinant of the future health of UK freshwater ecosystems.

Given the inherent complexity of water accounting, few studies have attempted to quantify such water flows. Roson & Sartori (2010) use a computable general equilibrium (CGE) economic model to identify the effects that embodied water trading in agricultural products has on GDP under wet, middle and dry climate change scenarios of mean annual runoff for 2050 in the Mediterranean region. They find that trade as an adaptation option facilitates increases in national GDP and net savings in embodied water. However, these gains are described as marginal; other public adaptation measures are highlighted as being required to more fully manage climate change-induced water resource constraints in the region. Konar et al. (2013) also use CGE modelling to identify trade-related water savings at the global scale for rice, oil seeds (soy) and wheat and use 3 crop productivity scenarios that account for precipitation, evapotranspiration and carbon dioxide (CO_2) fertilisation in 2030. They also find that there are water savings to be realised through international trade, and argue that these savings should be realised through reduction of existing trade barriers.

Whilst these studies identify potential trade effects at the regional and global scale, the level of aggregation does not allow for analysis of national-scale responses within relevant sectors and sub-sectors. The present study therefore seeks to provide a more disaggregated analysis of potential climate change risks to the trade in embodied water, with the intention of facilitating a discussion of the alternative responses an importing country can implement or promote by way of adaptation, additional to trade expansion.

2. DATA AND METHODS

We characterise our methods in the following series of steps. (1) We identify 25 sub-sectors that are both water-intensive and economically significant in terms of aggregate UK trade flows. (2) For each commodity, we calculate the average water consumption embodied in UK imports by country of origin. (3) We categorise these exporting countries according to a measure of current water scarcity. (4) We match these patterns of water consumption to regionally disaggregated climate change impacts projected for a time period centred on 2040. These steps enable the classification of current (2010) and future (2040) sectoral susceptibility to water scarcity and reveal the least water-secure donor regions. For illustrative purposes, we show the susceptibility of embodied water flows to climate change under the SRES A1B emissions scenario, generated by the Met Office Hadley Centre model HadCM3.

2.1. Step 1: identification of significant sub-sectors

A sample of trade sub-sectors[1] was identified on the basis of a mapping process that plotted the economic significance of all sub-sectors (measured by import value) against the sensitivity to climate of the production activities within the sub-sector. Further details of this mapping process are provided by Watkiss & Hunt (2012). As a result of this mapping, UK import data (by value and weight) for key countries of origin—i.e. those countries that currently provide at least 5% of

[1]Sub-sectors may comprise of a single commodity or a number of commodities

Table 1. Sub-sector commodities with country-specific example data of per tonne embodied water in commodity production exported to the UK and including principal data sources

Commodities	Examples: Product	Examples: Country	Examples: Embodied water	Data source(s)
Crops	Tomatoes	Spain	76 m^3 t^{-1}	Foresight Futures (2011), Watkiss & Hunt (2012)
Meat	Bovine	Ireland	6513 m^3 t^{-1}	Mekonnen & Hoekstra (2011)
Fish	Prepared/preserved fish	Thailand	15 m^3 t^{-1}	Hoekstra (2003)
Petroleum	Oil refining	Norway	2 m^3 t^{-1}	Seneviratne (2007)
Gas	Natural gas processing and transport	Qatar	0.11 m^3 GJ^{-1}	Gerbens-Leenes et al. (2008)
Coal	Coal mining	Russia	5 m^3 t^{-1}	Chi (2008)
Metal ores and scrap	Iron ore	India	0.27 m^3 t^{-1}	Tata Steel (2012)
Pharmaceuticals	Average of 5 analgesics	Germany	128 m^3 t^{-1}	Verma (2011)
Chemicals	Organic chemicals	Netherlands	40 m^3 t^{-1}	Environwise (2003)
Iron and steel	Steel manufacturing	France	3 m^3 t^{-1}	International Mining (2007)
Plastics	Polythene, polystyrene, polyvinyl	Belgium	8 to 500 m^3 t^{-1}	Katsoufis (2009), Morawicki (2012)
Paper	Paper and paperboard	Germany	300 m^3 t^{-1}	Morawicki (2012)
Electric current	Nuclear generated electricity	France	0.09 m^3 GJ^{-1}	Gerbens-Leenes et al. (2008)

UK imports of a given commodity (group)[2]—were extracted from the UN Comtrade database[3] for the sample of 25 sub-sectors identified as both climate-sensitive and economically significant. Overall, our sample of commodities represents 31% of the total import value to the UK in 2010. Amongst the chosen sub-categories, the most important in terms of value to the UK economy were petroleum (9%), pharmaceuticals (4%), manufactured chemicals (4%), organic chemicals (3%) and gas (2%). Other economically important sub-sectors (such as construction, financial services, information technologies, media and communication) are assumed to be climate insensitive and were not included in the analysis. The method of sampling adopted necessarily means that many commodities are excluded from the analysis, including product groups such as green beans, flowers and bottled water, that have received attention in the wider 'food miles' literature (Pretty et al. 2005).

2.2. Step 2: quantification of embodied water in import sub-sectors

Published water consumption unit estimates (in m^3 t^{-1}) for each commodity group were used to calculate the total water consumption for UK imports of those commodities by the key countries of origin. Sources of data on unit water consumption estimates for different commodity groups are given in Table 1, along with country-specific examples of per tonne water consumption associated with these commodities. In general, country-specific values are available for water consumption per tonne of product for crops and meat but not for fish and industry, in which case generic regional data were used. Fig. 1 (upper panel)

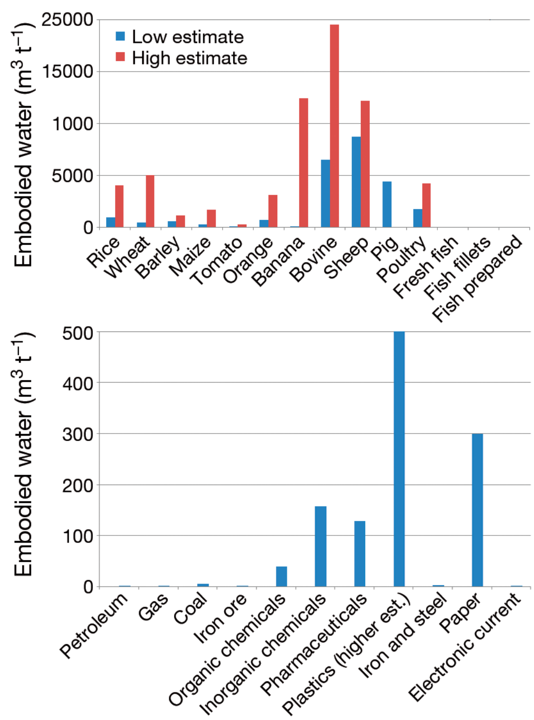

Fig. 1. Embodied water estimates for selected agricultural and fishery products (upper panel) as well as fuels, minerals, chemicals and manufactured products (lower panel)

[2]This metric is adopted to make the size of the analysis manageable and to ensure that focus on currently important exporting countries to the UK is retained

[3]United Nations Commodity Trade Statistics Database: http://comtrade.un.org/db/default.aspx

presents unit (m^3 t^{-1}) estimates for agricultural and fishery products used to calculate the total water consumption embodied in UK imports of these products. Lower bound estimates tend to be defined by imports from European countries, whereas higher estimates refer to imports with origins in other continents. In the case of bananas, the highest estimate is an anomaly (Hoekstra & Hung 2002) and refers to the water consumption for St Lucia of over 12 000 m^3 t^{-1}, compared with <1000 m^3 t^{-1} from most other countries.

Fig. 1 (lower panel) shows per tonne water consumption estimates for selected fuels, minerals, chemicals and manufactured products that are then used to calculate the total water consumption embodied in UK imports of these products. These single representative estimates for each product are used for imports from all the selected countries of origin. Fig. 1 shows a higher estimate of 500 m^3 t^{-1} for plastics, but calculations were also performed using a lower estimate of 8 m^3 t^{-1}. This large range reflects a variation in water use estimates for different forms of plastic or industrial processes. For example, whilst Morawicki (2012) presents values of 500 m^3 t^{-1} for polyethylene, polystyrene and polyvinyl chloride, Katsoufis (2009) estimates 8.7 m^3 t^{-1} for polyethylene and 8.27 m^3 t^{-1} for polypropylene.

2.3. Step 3: categorisation of exporting countries by current level of water scarcity

Current levels of water scarcity in countries exporting to the UK were classified using a widely recognised indicator of water stress (Falkenmark et al. 1989). Countries were defined as not water vulnerable (>2500 m^3 $ind.^{-1}$ yr^{-1}), vulnerable (1700 to 2500 m^3 $ind.^{-1}$ yr^{-1}), stressed (1000 to 1700 m^3 $ind.^{-1}$ yr^{-1}) or water scarce (<1000 m^3 $ind.^{-1}$ yr^{-1}).

2.4. Step 4: matching sub-sectoral embodied water with climate change risks

To assess future climate susceptibilities of activities in sub-sectors currently exporting to the UK, data on current import value and water use for the selected sectors identified in Step 1, above, were combined with information on climate change. Specifically, future climate risks identified as potentially significant to water resource availability (Table 2) were first graded using the matrix in Tables 3 & 4 before being matched to the country-specific sub-sector data.

Table 2. Examples of climate risks affecting production in different sectors in countries exporting to the UK. Adapted from Lewis et al. (2010)

Climate risks	Effect
Agriculture	
CO_2 fertilization higher minimum temperatures	Crop yield
Sea level rise	Arable area
Salt water intrusion	Crop yield
Storm and flooding	Damages crops
Droughts and changing seasonality of snow/ice melt	Water security
Hot spells	Crop yield and quality
Livestock	
Sea level rise and salt water intrusion	Pasture area
Storm and flooding	Impaired feeding
Drought	Pasture
Less frequent freezing	Hypothermia and dehydration of stock
Higher winter temperatures	Pests and disease
Hot spells	Heat stress
Manufacturing	
Sea level rise and salt water intrusion	Fresh water supply
Storm and flooding	Damage to infrastructure
Changing seasonality of snow/ice melt and drought	Water security
Surface runoff	Water storage and reliability
Drought	Water security and power generation
Higher temperatures	Water demand and conflict
Petroleum and gas	
Sea level rise and surge	Rig stability and disruption
Storm and flooding	Disruption and infrastructure damage
Drought	Efficiency of extraction
Higher temperatures	Ice on rigs
Drought	Subsidence

Climate risks were identified for one set of climate scenarios, reflecting data availability. However, it is well known that climate model scenarios show very different geographical patterns of change, particularly for precipitation, which is considered to be the most important driver of freshwater resources. Total uncertainty in global precipitation (and temperature) projections is conventionally divided into natural (internal) climate variability, climate model (structure and parameter) uncertainty and radiative forcing (scenario) uncertainty. Depending on the region, natural climate variability contributes 50 to 90 % of

Table 3. Classes of climate change impact severity and uncertainties adapted from Lewis et al. (2010)

Degree of uncertainty	Magnitude of impact			
	Minimal impact (0)	Low impact (1)	Medium impact (2)	High impact (3)
Changes unknown (A)	A0	A1	A2	A3
Some signal (B)	B0	B1	B2	B3
Strong signal (C)	C0	C1	C2	C3

the total uncertainty over the next decade and remains the dominant source of uncertainty for 30 yr (Hawkins & Sutton 2010). Following the Foresight Futures project (Lewis et al. 2010), we refer to scenarios generated by an ensemble of Met Office Hadley Centre model HadCM3 experiments under SRES A1B emissions scenarios to 2040. Climate change scenarios were then matched geographically with the world regions from which UK imports originate. World commodity regions were categorised into standard climate zones using the Giorgi & Francisco (2000) regions.

Finally, potential climate risks were classified by expected severity and degree of uncertainty of impacts by 2040 (Table 3). The 2-dimensional classification was based on expert judgement as in the Foresight Futures project (Lewis et al. 2010). Uncertainty was classified on the basis of the strength and consistency of the climate signal for specific climatic variables as indicated by the output of a 17-member ensemble of HadCM3. The impact on individual commodities was classified subjectively based on a variety of (positive and negative) risks to production (Table 2). We capture not only the direct effects on water resources as a result of changing precipitation patterns but also some potential indirect impacts that might, for example, arise from temperature changes influencing crop evapotranspiration. The combined data are then presented at a country level for 5 products that are responsible for the most significant volumes of water use in UK imports in areas of potentially increasing water scarcity. Thus, the total water consumption from producing the goods for export to the UK is estimated, alongside the projected future climate risks associated with these goods in the exporting countries.

Table 4. Classes of water availability (per person [ind.]) based on current (2010) water scarcity categories used by the United Nations Environment Programme (www.unep.org/dewa/vitalwater/jpg/0221-waterstress-EN.jpg)

	Not vulnerable (>2500 m^3 ind. yr^{-1})
	Vulnerable (1700–2500 m^3 ind. yr^{-1})
	Stressed (1000–1700 m^3 ind. yr^{-1})
	Water scarce (<1000 m^3 ind. yr^{-1})

The methods adopted in the present study are based primarily on observed data. Consequently, the results for future time periods must be inferred from present patterns of trade. For maximum transparency, Table 5 provides an evaluation of the individual methodological steps, with attendant assumptions, and acknowledged limitations of our approach.

3. RESULTS

3.1. Current embodied water imports

The full set of aggregate, country-based statistics by commodity are shown in Tables S1 to S25 in the Supplement at www.int-res.com/articles/suppl/c059p089_supp.pdf. Here, we concentrate on the 5 most important water uses in volumetric terms as well as on the overall susceptibility across the 25 sub-sectors considered.

Fig. 2 shows the total embodied water in all selected UK imports. It is evident that bovine meat production, plastics and paper production contribute the largest quantities of embodied water, in absolute terms, of the 25 import categories considered. Together, these imports account for ~40 % of the 12.8 billion m^3 of embodied water in these 25 categories. Rice and other meat categories (poultry, pig and sheep) account for a further one-third of the total.

These results confirm findings of previous studies showing the high relative significance of the contribution of crops and livestock to the total water footprint of UK imports (Chapagain & Hoekstra 2008, Chapagain & Orr 2008, Feng et al. 2011). In the case of the crop imports studied, we estimate total virtual water flows to be ~4 billion m^3 yr^{-1}, whilst the comparable value for livestock is ~5 billion m^3 yr^{-1}. These values compare with an aggregate of 43 to 46 billion

Table 5. Evaluation of study methods

Methodological step	Assumptions	Limitations
Identification of significant sub-sectors	Selected subsectors are representative of those imports to the UK that are most sensitive to water-related climate change risks. The countries focused upon according to current shares of UK import trade are assumed to be those who will continue to export to the UK	The selection of the subsectors is based on (1) those currently economically important (on the basis of import value) and (2) those that are currently climate-sensitive. The subsectors chosen by both criteria may change in future time-periods as economic and technological development proceeds.
Quantification of embodied water in subsectors	Data on current subsectoral per tonne water consumption is representative of water use intensities in future time-periods	Sub-sectoral water use intensities represent current patterns. However, these may change in the future in the face of technological change. Indeed, the countries of import origin may change with developments in future trade, thereby changing the relevant water use intensities.
Categorising exporting countries by current water scarcity	The indicators of water scarcity chosen (m^3 ind.$^{-1}$ yr^{-1}) are assumed to reflect the relative water scarcity faced by the selected subsectors in the relevant countries	The water scarcity indicators are country-specific. They would therefore not capture sub-national differences in water scarcity resulting from geographical variations at this scale.
Matching subsectoral embodied water with climate change risks	Future projections of climate change risks adopted in the analysis are plausible	The set of climate change risks identified for use in this analysis are taken from one climate scenario and therefore do not reflect the full range of uncertainties attendant to current projections. The results are only illustrative of potential susceptibilities.

m^3 yr^{-1} for embodied water in all crops and livestock—domestically produced and imported—for consumption in the UK (Chapagain & Hoekstra 2008, Chapagain & Orr 2008). To put these quantities into perspective, the total amount of water abstracted in the UK for all agricultural uses was 7.7 billion m^3 in 2006, equivalent to one-fifth of the water utilised in the production of agricultural products for export to the UK. Thus, it is clear that there is a substantial water deficit resulting from the patterns of embedded water in agricultural products consumed in the UK.

Embodied water estimates for UK industrial product imports are much less developed than for crops and livestock, reflecting their low importance in absolute terms. Based on crude assumptions, earlier studies claim that the embodied water in these imports is in the range of 17.2 to 20 billion m^3 yr^{-1} (based on statistics for 1997 to 2001) (Chapagain & Hoekstra 2008, Chapagain & Orr 2008). By comparison, total embodied water in domestic production of industrial products is <32 billion m^3 yr^{-1} (Yu et al. 2010). Even though our study focused on a few selected products, our estimates demonstrate that paper (1.7 billion m^3 yr^{-1}) and plastics (1.5 billion m^3 yr^{-1}) constitute a significant proportion of the total embodied volumes. We

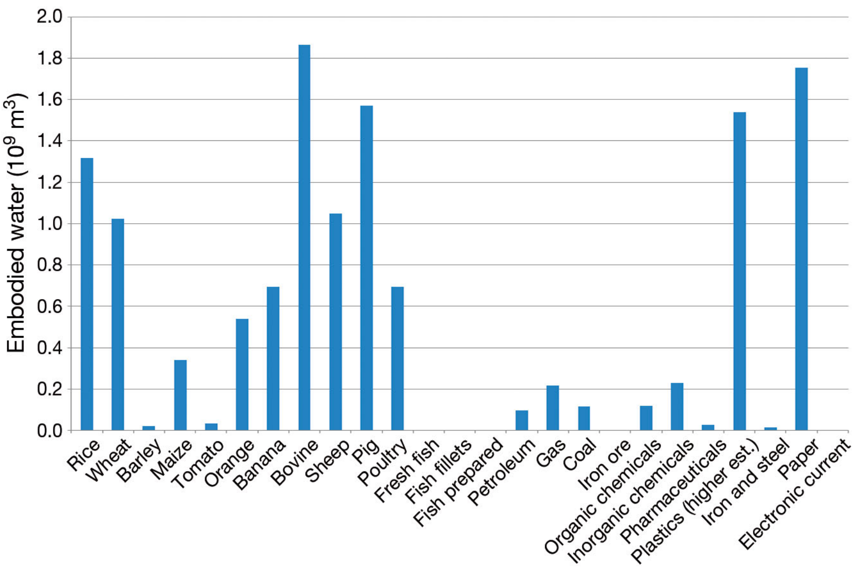

Fig. 2. Total water volumes embodied in selected UK imports (2010)

also compared the relative importance of these sectors utilising both the economic and water metrics, expressed in fractional terms. Fig. 3 shows that whilst the dominant economic sectors are energy and manufacturing, with the exception of paper and plastics, the major water-consuming sectors are agricultural. This confirms the finding of previous research (Chapagain & Hoekstra 2008).

3.2. Future embodied water imports

Country-level results are based on water scarcity data provided by the United Nations Environment Programme (UNEP 2008) (Tables S1 to S25 in the Supplement). This reveals current exporters with water scarcity in North Africa and the Middle East, plus areas of water stress in East and South Asia (notably China and India), Eastern and Southern Africa and some European countries, including Poland and Denmark. In the future, a major additional factor in determining global water stress is population size. United Nations (2004) projections suggest that the current upward trend in global population will continue until at least 2030; the medium projection is for a population of 8.9 billion by 2050, compared to 7 billion in 2012, representing an increase of 28 %.

Other regions are expected to become water-stressed in coming decades. One seminal study suggested that under a variety of economic and demographic scenarios to 2025, 2055 and 2085, even in the absence of climate change, populations in East and West Africa, Central Asia and Central America could become increasingly water stressed (Arnell 2004). When climate change scenarios were taken into account, water stresses increased in other areas including the Mediterranean, parts of Europe, Central and Southern America and Southern Africa.

The 5 most important water uses, in volumetric terms, are rice, bovine meat, pig meat, plastics and paper and paperboard (see summary results for these sub-sectors in Tables 6 to 10 and full results in Tables S1 to S25 in the Supplement), though the high ranking of plastics reflects the use of the upper end of the per tonne water consumption range; use of the lower-end value results in plastics being ranked 20th out of the 25 sub-sectors considered. Together, these commodities constitute ~60 % of the 12.8 billion m^3 of the embodied water in our chosen imports. The total value (US$) and water consumption (m^3) of the given commodity imported to the UK from key countries of origin were calculated along with the total import value from all countries of origin for the year 2010. Note that our results for 2040 are specific to the chosen climate scenario and that where no class is given in Tables S1 to S25, information on the specific climate risk was not available.

India and Pakistan are the largest exporters of rice to the UK in monetary and water volume terms, currently accounting for almost 40 % of the total rice import value. However, Table 6 shows that compared to Thailand, these countries are the least water-efficient rice producers exporting to the UK. This inefficiency likely results from the substantial subsidies given to irrigation in these countries that distort the true opportunity costs of rice production in South and

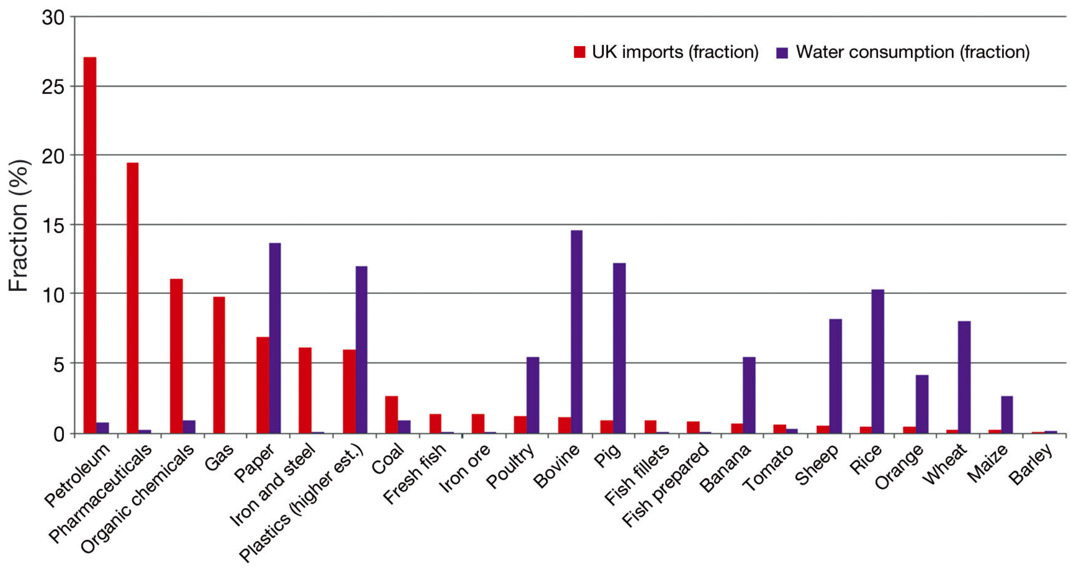

Fig. 3. Fractional economic value and water consumption for selected UK imports in 2010

Table 6. Climate change risks and embodied water in UK imports: rice. CO_2 fert.: CO_2 fertilisation; salt water: salt water intrusion risk to crops; storm: storm risk to crops; melt patterns: reduced water availability from changing melt patterns; flood: flood risk to crops; drought: risk of drought to crop yield; hot spells: vulnerability of crops to hot spells; min temps: risk of higher minimum temperatures to crop yield; total consump.: total water consumption associated with UK imports (m^3)

Country	Total consump.	Min temps	Hot spells	Drought	Flood	Melt patterns	Storm	Salt water	CO_2 fert.
Europe & Med									
Spain	118 020 465	C3	C3	A3	A3		A3	B2	C2
Italy	71 697 270								
NL	32 090 990			B3					
Belgium	16 666 664								
North America									
USA	76 205 074	C3	C3	A3	A3		A3	B2	C2
East Asia									
China	115 776	C3	C3	A3	A3	A3	A3	B2	C2
Southeast Asia									
Thailand	246 268 044	C3	C3	A3	A3		A3	B2	C2
Vietnam	207 648			A3	A3		A3		
Central & S. America									
Uruguay	18 097 317	C3	C3	A3	A3	A3	A3	B2	C2
Argentina	286 300			B2					
South Asia									
India	413 634 550	C3	C3	A3	A3	A3	A3	B2	C2
Pakistan	325 057 831								

South-East Asia (Rosegrant et al. 2002). Moreover, national-level statistics can conceal strong regional variations. For example, it is known that despite current water stress, rice is grown extensively in the Punjab region to generate export earnings that constitute an income that is higher than from alternative uses of the water (Kumar & Jain 2007), a finding that serves to emphasise that water is only one of a number of factor inputs that influence the viability of rice production. When we consider sensitivity to climate change, it is clear that the majority of climate risks are judged to have potentially high impacts, though the precipitation-driven risks have a high degree of uncertainty (category A3). In contrast, temperature-related risks are projected with greater likelihood to increase evapotranspiration, affecting rice growth and yields (category C3).

Fig. 3 shows that bovine and pig imports are important components of UK embodied water. Ireland currently accounts for over two-thirds of the total bovine meat import value to the UK (Table S8). Other significant exporters are from Central and South America, Africa, and Australia and New Zealand. Table 7 shows that water efficiency differs among these world regions, with European countries being 2- and 3-fold more efficient than Africa/Australia and Central/South America, respectively. The severity of the future climate risks that these regions are projected to face in relation to bovine meat production does not differ geographically. Across all regions, the effects of heat stress—which could increase demand for water cooling—is judged to be both the most severe and most likely climate risk (Mader 2003). The same result is found for pig meat exports to the UK (Table 8), where Denmark and Netherlands are the largest exporters to the UK (Table S10).

The 2 most water-sensitive manufacturing commodity groups are paper and plastics (Tables 9 & 10, Tables S22 & S23). European countries including Germany, Belgium and Netherlands account for ~50% of the total import value of plastics to the UK. Since there is no differentiation between water demand levels between countries — though S22 shows a substantial potential range in the level of efficiency assumed, reflecting different types of plastic products as well as alternative processes — these countries also account for the majority of water use in volumetric terms. Potentially the most severe risk is from greater drought frequency and intensity, with indirect impacts on manufacturing processes and power generation if, for

Table 7. Climate change risks and embodied water in UK imports: bovine meat. Salt water: salt water intrusion risk to grazing pastures; flood: risk of flooding causing feeding difficulties; summer rain: risk of lower summer rain reducing growth of pasture plants; freeze events: reduced freezing of water reduces hypothermia and dehydration risks; warm winters: risk of increase in disease and pests as a result of warmer winters; heat stress: risk of heat stress negatively affecting animal health and productivity

Country	Total consump.	Heat stress	Warm winters	Freeze events	Summer rain	Flood	Salt water
Europe & Med							
Ireland	1 094 672 475	C3	B2	C2	B2	A2	B2
Netherlands	97 714 539						
Germany	48 769 344						
Italy	20 235 891						
Belgium	17 904 237						
Poland	12 140 232						
France	18 060 549						
Spain	15 520 479						
Denmark	6 929 832						
Central & S. America							
Uruguay	175 353 024	C3	B2	C2	C2	A2	B2
Brazil	37 475 424						
Africa							
Namibia	114 918 825						
Botswana	97 977740						
Australia & NZ							
Australia	64 629 774	C3	B2	C2	B2	A2	B2
New Zealand	42 281 870						

Table 8. Climate change risks and embodied water in UK imports: pig meat. Table headers as for Table 7

Country	Total consump.	Heat stress	Warm winters	Freeze events	Summer rain	Flood	Salt water
Europe & Med							
Denmark	441 832 611	C3	B2	C2	B2	A2	B2
Ireland	206 776 723						
NL	285 621 781						
Germany	214 301 594						
Belgium	215 320 264						
France	133 202 175						
Spain	72 081 975						

example, some form of rationing of use was introduced. The same results are found for paper and paperboard, for which the 2 dominant exporters to the UK are Germany and Sweden, which are also judged to be vulnerable to drought (category B3).

4. DISCUSSION

The 5 sub-sectors highlighted above provide several important insights. First, it is clear that they reflect diverse but economically important commodity groups that are sensitive to a range of climate change risks that vary in projected severity and likelihood. It is also clear from the scenario-based analysis that the susceptibility of production of UK imports of these commodities to changing patterns of precipitation is less certain than the susceptibility to changes in temperature. However, it is also evident that these 2 sets of climatic variables need to be viewed together because production is potentially affected by an inter-play of multiple climate as well as non-climatic pressures. Semenov et al. (2012), for example, show that both annual means and extreme weather events associated with precipitation and temperature are critical to wheat production. They also highlight the influence of technologies on agricultural productivity judged likely to interact with climatic factors in future time periods.

Both imported and domestic UK production could be simultaneously impacted by extreme weather events. For example, bovine meat from Ireland equates to 71 % of the import tonnage and 59 % of the embodied water (from the selected countries). Given the geographic proximity of Ireland to the UK, whenever the former is impacted by heat waves, it is reasonable to expect that the latter (and other nearby producers in northwest Europe) could be similarly affected. Therefore, the supply reduction created by this type of weather, and consequent upward impact on consumer prices for the commodity, could be even more serious than Table 7 suggests. The same issue applies to UK and Europe-wide pig meat (Table 8), paper (Table 9) and plastics (Table 10) production. Furthermore, it is likely that these neighbouring states would be competing with the UK to secure the same commodities from sources outside Europe.

The static approach adopted contrasts with previous macro-economic analyses of embodied water in trade flows by making explicit the range of climate change effects which the exporting country sub-sectors will need to consider and perhaps respond to

Table 9. Climate change risks and embodied water in UK imports: paper. Salt water: risk of salt water intrusion; storage: changes in precipitation affecting availability and storage of water; precipn.: risk of water stress from precipitation changes; run-off: greater surface runoff enhancing water availability; drought: drought limits production and power generation; high temps.: risk of high temperature creating greater demand for water and increasing conflict between water-use groups

Country	Total consump.	High temp.	Drought	Run-off	Precipn.	Storage	Salt water
Europe & Med							
Germany	5 649 472	B1	B3	B1	A2	A2	C1
France	3 159 000						
Spain	612 120						
Italy	905 072						
Switzerland	37 176						
Netherlands	5 135 248						
Belgium	6 440 952						
Ireland	446 712						
Sweden	344 856						
Czech Republic	141 048						
Poland	189 504						
Austria	200 728						
North America							
Canada	4 864	B1	B3	B1	A2	A2	C1
USA	732 808						
East Asia							
China	112 200	B1	B3	B1	A2	A2	C1
Japan	106 440						
S. Korea	176 136						
Southeast Asia							
Malaysia	19 040	B1	B3	B1	A2	A2	C1
Thailand	116 336						
Central & S. America							
Mexico	67 752	B1	B3	B1	A2	A2	C1
South Asia							
India	20 208	B1	B3	B1	A2	A2	C1

Table 10. Climate change risks and embodied water in UK imports: plastics. Column headers as in Table 9

Country	Total consump.	High temp.	Drought	Run-off	Precipn.	Storage	Salt water
Europe & Med							
Germany	470 640 400	B1	B3	B1	A2	A2	C1
France	209 198 010						
Spain	60 977 476						
Italy	86 999 621						
Switzerland	1 523 969						
Netherlands	119 687 103						
Belgium	58 858 964						
Ireland	14 947 406						
Sweden	412 755 138						
Czech Republic	14 663 357						
Poland	35 459 434						
Austria	61 475 193						
North America							
Canada	53 294 270	B1	B3	B1	A2	A2	C1
USA	70 358 403						
East Asia							
China	69 189 183	B1	B3	B1	A2	A2	C1
Japan	1 524 204						
S. Korea	2 600 687						
Southeast Asia							
Malaysia	1 894 769	B1	B3	B1	A2	A2	C1
Thailand	320 327						
Central & S. America							
Mexico	276 803	B1	B3	B1	A2	A2	C1
South Asia							
India	7 458 270	B1	B3	B1	A2	A2	C1

in their activities. The analysis is country-specific in both the fact that the value of these imports is important to the UK and that the country of origin is identified. Therefore, the analysis is designed to highlight that current trade partners of the UK may be impacted by climate change and that to retain this export market, they may need to place increasing emphasis on water management. Alternatively, to maintain export earnings, these countries may consider diversification into less water-intensive industries. Conversely, the UK may wish to protect the supply of certain commodities from specific countries, or at certain cost levels, in which case the climate adaptation strategy would need to adopt an international dimension that encourages water management measures in the countries exporting these commodities to the UK. Alternatively, the UK could begin to consider developing new trade relationships with countries that are likely to be less negatively impacted by climate change and that would therefore provide either a lower-cost or more reliable supply of commodities.

Our analysis provides an indicative, broad-brush, impression of UK import susceptibilities to international climate change risks. Several future research priorities emerge from this high-level scoping of the susceptibility of UK import production to climate change-induced water scarcity. (1) A greater range of country- or region-specific climate change scenarios could be explored for the most climate-sensitive import sectors. (2) More detailed commodity-focussed case studies could be undertaken that utilise quantitative climate change analysis to estimate the potential scale of these future risks relative to current water sensitivities. (3) Indices of embodied water could be developed that incorporate measurement of water scarcity in regions within countries, both for current and future climate scenarios. These indices would benefit from making the distinction between the different sources of water used in production, i.e. directly rain-fed water (known as 'green water') and water from water courses and aquifers ('blue water'), and from incorporating a measure of the differential opportunity costs associated with these sources. This research would therefore down-scale existing global-level analyses reported by, for example, Rost et al. (2008) and Konar et al. (2012).

In due course, UK international development/adaptation strategies might target areas from which UK imports currently originate or encourage alternative trade partnerships in less climate-sensitive regions, thereby reducing the susceptibility of supply. Following from this (4) an important research priority is to explore alternative adaptation options/strategies in a number of case study contexts in which climate change is projected to significantly alter water resource availability in domestic production and in which a region or country has a particular exposure to water-embodying exports.

In support of these research priorities, it would also be useful to explore the extent to which the aggregate form of CGE macro-economic modelling undertaken by Konar et al. (2013) could be tailored, thereby allowing a move away from a static analysis to a more dynamic form of analysis. For instance, such modelling could be used to identify for what commodity-climate scenario combinations it is advantageous, given current and plausible future trade partnerships, for a major importing country such as the UK to invest in supporting existing export partners and/or to encourage diversification of trade partners. Such dynamic modelling approaches will be rendered a great deal more realistic if — as identified in Table 5 — the constraints imposed by our use of current, observed, data are relaxed by the use of scenario-generated data sets relevant to each of the main methodological steps adopted in the analysis.

5. CONCLUSIONS

The UK is susceptible to pressures on global water resources because the national water footprint and water import dependency are relatively high even before climate change and population growth are considered. Without aggressive water-saving and efficiency measures or compromised environmental quality, there is limited scope for substitution of imported goods by domestic production unless there are price increases, though, of course, the market economy allows for substitution of goods and trade partners, with their own associated economic welfare losses. Likewise, some of the UK's most important water-trading partners (notably Denmark, Ireland and Germany in Europe — responsible for exporting the highest quantities of embedded water in pig meat, bovine meat and plastics, respectively, to the UK — and India and Pakistan in South Asia, responsible for the highest quantities of embedded water in rice exports to the UK) are similarly water scarce and facing increasing scarcity from climate change in the future. Climate change-induced adjustments in international comparative advantage are therefore likely to lead to evolving trade patterns and relations. Hence, climate risks to the UK water balance — and to those countries with similar susceptibilities — will need to be managed alongside other, better understood, drivers of demand, including terms of trade, demographics, consumer behaviour and dietary trends, policies surrounding national food security, environmental standards and competing land uses.

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