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# Food-energy-water nexus: A life cycle analysis on virtual water and embodied energy in food consumption in the Tamar catchment, UK

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ABSTRACT

Evaluations of food, energy and water (FEW) linkages are rapidly emerging in contemporary nexus studies. This paper demonstrates, from a food consumption perspective, the potential of life cycle thinking in understanding the complex and often “hidden” linkages between FEW systems. Our study evaluates the upstream virtual water and embodied energy in food consumption in the Tamar catchment, South West England, distinguishing between domestic production and imports origin. The study also evaluates key inputs, including virtual nutrients and animal feed, when tracking supply chain of food products. Based on current dietary patterns and food products selection, the catchment consumes annually 834 TJ, 17 $hm^3$ and 244 $hm^3$ of energy, blue water and green water, respectively. Tamar is not self-sufficient in terms of food and requires imports of food products, as well as imports of virtual nutrients and animal feed for local production. Consequently, 51% of the embodied energy and 88% blue and 45% green virtual water in food consumed within the catchment are imported. Most of the embodied energy (58%) and green virtual water (90%) are because of animal feed production, where nearly half of embodied energy (48%) and green virtual water (42%) come from imports. 92% of blue virtual water is used for irrigation and primarily happens elsewhere due to imports. Irrigation is the process that demands the largest amount of energy for the crop-based products, with 38% of their total energy demand, followed by fertilisers production (24%). Our study illustrates water and energy hotspots in the food life cycle and highlights potential FEW risks and trade-offs through trade. This is useful considering potential unexpected changes in trade under recent global socio-political trends. Currently available databases and software make LCA a key tool for integrated FEW nexus assessments.

## 1. Introduction

Food security in the UK relies significantly on production in other countries and food imports account for about 50% of the total food supply in terms of calorific value (de Ruiter et al., 2015). This reliance is not limited to the food products, but also applies to key inputs during the food life cycle. For example, UK fertiliser consumption was more than twice that of domestic production between 2010 and 2014 (FAOSTAT, 2017a). Moreover, avoidance of extracting local natural resources displaces environmental pressure through trade, i.e., the environmental pressure takes place in another country rather than the country of final consumption. In this regard, UK is the most significant in the EU, displacing about 48.2 $MtCO_{2e}$, 18.2 Mha and 1078 $hm^3$ of its carbon, land and blue water footprints, respectively (Steen-Olsen et al., 2012).

Food production requires a wide range of resources, with water and energy being the key inputs to various processes along the food supply chain (e.g., production of crop and livestock, food processing, manufacturing, storage and distribution). With growing attention on Food-Water-Energy (FEW) nexus tools and data availability (McGrane et al., under review), there is a need for more integrated evaluations of water and energy consumption for food. Life cycle assessment (LCA) is a key tool commonly used to quantify and compare the environmental impacts of different products or activities over their entire life cycle and has helped inform decision making in many areas (Hellweg and Canals, 2014). LCA has been extensively applied to analyse agricultural production (Nemecek et al., 2016), but the majority of studies have focused on resource efficiency and environmental impacts of different production systems. More recently a few studies have assessed the environmental implications of different diets and food consumption patterns (De Laurentiis et al., 2016; Nemecek et al., 2016). However, these LCA studies tend to focus particularly on greenhouse gas (GHG) emissions

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(Virtanen et al., 2011; Pairotti et al., 2015; Green et al., 2015; Heller and Keoleian, 2015; Milner et al., 2015) or land occupation (Saxe, 2014; Hallström et al., 2015; Tom et al., 2016). The coverage of environmental assessments of water use in LCA studies has mainly limited to specific food products (Canals et al., 2008; Milà i Canals et al., 2010; Page et al., 2011; Elisabet et al., 2017) or food production systems (Tallentire et al., 2017).

We believe LCA can be a powerful and readily available tool for uncovering interconnections between processes and products and with the environment in the context of food-energy-water (FEW) nexus evaluations. Moreover, there is rich information behind several LCA databases, including Agri-footprint, ecoinvent or AGRYBALYSE, and this readily available information can be key to further evaluate key, and also sometime omitted, flows in FEW studies of food products. LCA has already been widely used in FEW nexus studies on, e.g., water consumption and impacts during the production of biogas from energy crops (Pacetti et al., 2015), carbon emissions in water utilities and supply (Venkatesh et al., 2014; Fang et al., 2015), water consumption and carbon emissions in Chinese electricity production (Feng et al., 2014) and environmental impacts of water and energy supply scenarios (Dale and Bilec, 2014). There is a growing FEW nexus literature which adopts a LCA thinking on food systems. For instance, Jeswani et al. (2015) look at the global warming potential and water footprint of breakfast cereals and snacks, whereas Vora et al. (2017) focus on the embodied irrigation energy and GHG emissions in food trade for the United States. Another example is an environmental assessment for a food production system by Al-Ansari et al. (2015) using a series of subsystems for agriculture, water and energy. Moreover, Ramaswami et al. (2017) applies a life cycle thinking for the FEW nexus of Delhi, where in-boundary and trans-boundary production of FEW are shown. Efforts have also been made to integrate LCA into the broader context of the use of natural resources for food and energy and the associated effects on ecosystems services (Karabulut et al., 2018).

In the scientific literature there are different uses of the terms ‘embedded’, ‘embodied’ and ‘virtual’, which can be distinguished mainly depending on the resource under study (e.g., energy, water, nutrients) and scope (e.g. localized consumption, trade studies). Using virtual, embedded or embodied water has a similar meaning in the water literature (Hoekstra and Chapagain, 2008). There is also the term ‘water footprint’, which is similar to virtual water when considering the volumetric water footprint from the Water Footprint Network (WFN),[1] but is applied in the evaluation of localized water consumption rather than for trade studies (Hoekstra et al., 2011; Feng et al., 2012). In contrast, tracking energy in upstream supply chains is termed mainly as embodied (Beccali et al., 2013; Rocha et al., 2014; Motuziene et al., 2016). Regarding nutrients, ‘virtual’ nitrogen (and other nutrients) are those resources that are used in food production but are not physically contained in the final product (Lassaletta et al., 2013; Nesme et al., 2016; Shi et al., 2016). And ‘embedded’ is used when the resources are contained in the shipped product (Galloway et al., 2007; Schipanski and Bennett, 2012). Other studies have used the term ‘embodied’ phosphorus in trade analysis and included both the total phosphorus inflows and phosphorus contained in agricultural products (MacDonald et al., 2012). As a result, we use embodied energy, virtual water and virtual nutrients in our study, distinguishing between domestic and traded resources.

Based on this premise, this study shows the potential of LCA applications and ready available life cycle inventory (LCI) databases in FEW nexus studies from a food consumption perspective. The study aims to concomitantly evaluate the upstream virtual water and embodied energy flows for food products consumed in a catchment in South West England – the Tamar catchment. The work quantifies total virtual water and embodied energy, and also evaluates key inputs, including virtual nutrients and animal feed, when tracking supply chain of food products. For that our approach looks in detail at the processes and links of water and energy flows for the production of food products, making a spatial explicit distinction between the international food imports and imports of inputs to maintain local consumption within the catchment and those domestically produced and consumed in the catchment.

## 2. Material and methods

### 2.1. Site of study: the Tamar catchment in the context of the WEFWEBs project

This paper is framed within the ongoing work in the “Water Energy Food: WEFWEBs” research project (https://www.gla.ac.uk/research/az/wefwebs/). WEFWEBs maps different FEW nexus case studies in the UK over various spatial scales (catchment, city, household and company) and dimensions (biophysical, regulatory and social). Those case studies include Oxford and London, households in Newcastle, the Tamar catchment and a winery in South London. The project aims to understand and identify synergies between the different approaches and outputs from those case studies and LCA has been considered as a key tool for quantifying water and energy flows at different spatial scales within the project. A catchment case study was selected because it represents the scale at which water resources are assessed and managed. Although there are some FEW studies at the catchment scale, particularly for reconciling policy, management plans and decision support (e.g., for water, agriculture, energy) (Bizikova et al., 2013; Mayor et al., 2015), there is little LCA research at this level.

The Tamar catchment is located in the Devon and Cornwall counties in South West England, with an area of 1825 $km^2$ and a total population of about 300,000 inhabitants in 2011 (Westcountry Rivers, 2013). Agricultural land including pastures totals 136,000 ha and accounts for 75% of the catchment area. Pastures occupy about 72,050 ha, followed by barley, wheat and maize with 20,690, 15,720 and 9550 ha, respectively (EDINA, 2011; EEA, 2012).

### 2.2. Method

Our study uses readily available LCI datasets for food products from the Agri-footprint version 2.0 database (Blonk Consultants, 2015), included in the SimaPro version 8.2.3.0 software (PRé Consultants, 2016). We calculate annual food consumption in Tamar in both weight and calorific value (in kcal) for a population of 300,000 inhabitants, using 2013 as the reference year of study. The main food products purchased at a household level were obtained from the Survey of Living Costs and Food for the South West region (DEFRA, 2015). Eleven representative products were selected based on available LCI datasets within the Agri-footprint database out of eleven food categories that cover more than half (58% based on weight and 53% based on calorific value) of domestic food purchase (see Table 1 and Fig. A1 in Supplemental material). We believe that there is rich information readily available in several LCA databases, including Agri-footprint, ecoinvent and AGRIBALYSE that can be used relatively easily to offer new insights into the often underestimated or omitted resource flows in FEW studies. The final selection of our products was determined by the available data from the Agri-footprint database. We did not use products in other databases such as ecoinvent or AGRYBALYSE because of the varying assumptions used, e.g., on system boundaries and agricultural and irrigation modelling (Corrado et al., 2017).

The system boundary of the food products is cradle-to-gate, i.e., from crop cultivation to the factory gate. The retail phase, including the

[1] There is also the work from the LCA community's on water footprint, whose LCA developments have framed the main concepts in the international standard on water footprint (ISO 14046). The water footprint in the LCA community is defined as “metric(s) that quantifies the potential environmental impacts related to water” (ISO, 2014) and therefore does not primarily report the volume of water consumed, but the potential impacts caused (e.g., water scarcity).

**Table 1**
LCI datasets for food products available within the Agri-footprint database that match the food categories considered.

| Food category | Food product | Dataset available in Agri-footprint database | Quantity consumed per person and week | Unit | Kcal/100 g or unit | % of the total food purchase by weight | % of the total food purchase by kcal |
|---|---|---|---|---|---|---|---|
| Milk and milk products excluding cheese | Milk | Standardized milk, skimmed, from processing, at plant/NL Economic | 2105 | ml | 42 | 18 | 7 |
| Cheese | Cheese | Cheese, from cheese production, at plant/NL Economic | 135 | g | 323 | 1 | 3 |
| Carcase meat | Beef | Beef meat, fresh, from beef cattle, at slaughterhouse, PEF compliant/IE Economic/Economic | 226 | g | 174 | 2 | 3 |
| Non-carcase meat and meat products | Chicken | Chicken meat, fresh, at slaughterhouse/NL Economic | 786 | g | 106 | 6 | 7 |
| Eggs | Eggs | Consumption eggs, laying hens > 17 weeks, at farm/NL Economic | 2 | unit | 69 | 1 | 1 |
| Fats | Rapeseed oil | Refined rapeseed oil, from crushing (pressing), at plant/NL Economic | 146 | g | 884 | 2 | 12 |
| Sugar and preserves | Sugar | Sugar, from sugar beet, from sugar production, at Suiker Unie plants/NL Economic<br>Sugar, from sugar cane, from sugar production, at plant/BR Economic | 821 | g | 389 | 1 | 5 |
| Fresh and processed potatoes | Potatoes | Starch potato, at farm/DK Economic | 821 | g | 70 | 7 | 4 |
| Fresh and processed | Carrots | Carrot, at farm/NL Economic | 1240 | g | 35 | 10 | 4 |
| Flour | Wheat flour | Wheat germ, from dry milling, at plant/NL Economic | 60 | g | 330 | 5 | 2 |
| Other cereals and cereal products | Rice | Rice, late, continuous flooding, at farm/CN Economic | 538 | g | 136 | 4 | 6 |

*Note*: food consumption rate is based on a survey for South West England (DEFRA, 2015); it is assumed that UK sugar is produced with sugar beet, whereas imported sugar is made from sugar cane; calorific values for different food products are obtained from USDA (2017); it is assumed that density of milk is 1.03 kg/l and an egg weighs 56.7 g; BR (Brazil), CN (China), DK (Denmark), IE (Ireland), NL (The Netherlands).

packaging for consumer use, and the final consumption phase are outside of the system boundary, which also excludes transport after factory gate. High-level processes considered include animal feed inputs, fertiliser use, water and energy use (fuel, electricity and heat) on farm and in factory and transport of agricultural outputs to processing plants (Fig. 1). The temporal coverage of data collected in Agri-footprint is referred to as "mixed years", with references published from 2008 to 2015 (Blonk Agri Footprint BV, 2015). Due to data availability, LCI datasets for food products produced in neighbouring countries such as The Netherlands (milk, cheese, chicken, eggs, rapeseed oil, sugar from sugar beet, carrot, wheat flour), Denmark (potatoes) and Ireland (beef) were used when UK-specific datasets are not available in the database.

We use these LCI datasets to obtain the blue water (i.e., water from lakes, dams, rivers and aquifers) and energy per kg of food product, except for eggs which is by piece. Green water (i.e., rainfall source and consumed in the area where it falls) is not yet considered in the Agri-footprint database. In this study we have included green water consumption for croplands and pasture lands based on values from Mekonnen and Hoekstra (2010a,b). Average green water values for the Devon and Cornwall counties are used for domestic cropland production, whereas national values are used for imported crops and a global average for pasture lands. Green water is calculated for all the food products from crops produced for direct human consumption, e.g., potato and carrot or processed from crops, e.g., rapeseed oil (from rapeseed), sugar (from sugar beet or sugar cane) and wheat flour (from wheat). For animal products, green water is included for pasture, maize silage and crops required to produce compound feed.

The study also complements Agri-footprint with the energy requirements for irrigation based on data available in the ecoinvent database. Energy consumption per $m^3$ of irrigation water is available by country. The estimation of energy covers the activities of water pumping, machine infrastructure and a shed for machine sheltering. Irrigation data from ecoinvent provide a ratio of energy requirements for water withdrawn from surface and groundwater. When irrigation is not available for a country we use average global values.

Other studies that apply a consumption based approach make a distinction between the resource flows of produced within an area, imported from other regions within the country and imported by international trade (Erickson et al., 2012; Chavez and Ramaswami, 2013; Lin et al. (2015). In our study, imports from other UK regions are not considered due to the lack of available intra-national trade data. As a result, when we refer to domestic food production, it covers production within the catchment and other UK regions. After obtaining the blue virtual water ($m^3$), green virtual water ($m^3$) and embodied energy (J) by process and per unit of selected food product based on the LCI datasets, we calculate the virtual nutrients imports required to maintain Tamar consumption from domestic crop-based food products (i.e., rapeseed oil, sugar, potato, carrot and wheat flour). The virtual nutrients imports are calculated based on average imports of nitrogen (N), phosphate ($P_2O_5$) and potash ($K_2O$) for the period 2010–2014 (FAOSTAT, 2017c). The proportion of animal feed coming from overseas is also calculated for each animal product (i.e., milk, cheese, beef, chicken and eggs) (more details in Section 2.2.1). We then calculate the per capita and catchment total blue virtual water ($m^3$), green virtual water ($m^3$) and embodied energy (J) in domestic food consumption based on food purchased at a household level (Table 1). Finally, we determine the proportion of local production within the catchment and imports of food products from overseas based on trade data (FAOSTAT, 2017b; FAOSTAT, 2017c), using 2013 as the reference year (more details in Section 2.2.2). The ratios representing the proportions of overseas imports to maintain Tamar consumption are estimated on the assumption that fertilisers, feed and food production are homogeneous throughout the country and as a result a national level indicator is appropriate to be extrapolated to the catchment level. If the calculated ratios are larger than one, it is assumed that all consumption is

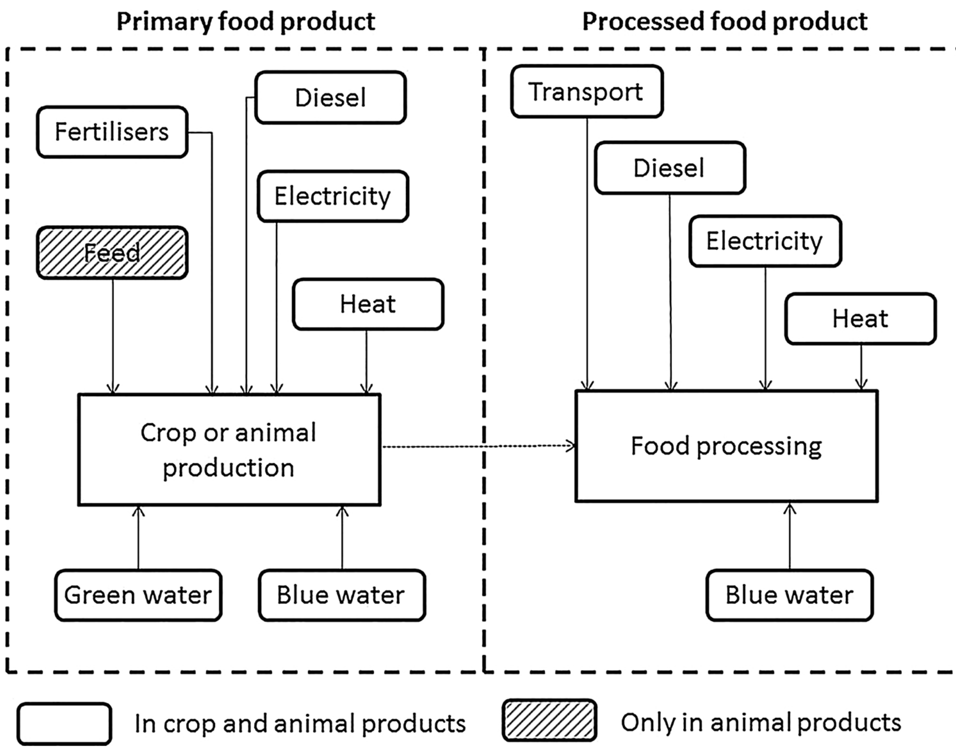


**Fig. 1.** System boundaries of the crop- and animal-based food products considered in the study.

maintained by overseas production and as a result there is no need to calculate the domestic production. This is the case when no domestic production occurs and a region imports more than the amount consumed, because some is exported.

### 2.2.1. Virtual water and embodied energy in virtual nutrients and animal feed

In this section, the amount of virtual nutrients and animal feed that are imported to maintain Tamar consumption from domestic agricultural production or on the contrary produced domestically will be determined. During the production of a crop, different fertilisers will be used, which are available in the Agri-footprint database as well as the related water and energy flows for each fertilizer used per crop. In the end, flows of water or energy consumption are aggregated for all fertilisers by crop.

***Virtual nutrients***

Our study tracks the international and domestic virtual nutrients of nitrogen, phosphorus and potassium, because of the known relevance that fertilisers have on energy and environmental implications. We assess the virtual nutrients in food products based on the total nutrients applied on field following previous studies (e.g., Nesme et al. (2016)) and we also distinguish the domestic use of nutrients from those imported through trade (MacDonald et al., 2012). To calculate the proportion of virtual nutrients coming from overseas, for each locally produced crop *i*, i.e., rapeseed (rapeseed oil), sugar beet (sugar), potato, carrot and wheat (wheat flour) the N, $P_2O_5$ and $K_2O$ nutrients are allocated between production within the country or outside. For each local crop *i*, the virtual water ($m^3$) or embodied energy (J) *k* in virtual nutrients from overseas ($fertiliser_{ik\ overseas}$) is calculated as:

$$virtual\ nutrients_{ik\ overseas} = \sum (fertiliser_{ijk} \times fert\ imp_j) \tag{1}$$

Where, $virtual\ nutrients_{ijk}$: virtual water ($m^3$) or embodied energy (J) *k* in fertiliser *j* and crop *i*, $virtual\ nutrients\ imp_j$: ratio between the amount of imports and consumption of nutrients for each fertiliser *j*.

For the calculation of $virtual\ nutrients\ imp_j$, imports and consumption quantities (t) of total nutrient contents for N, $P_2O_5$ and $K_2O$ fertilisers are obtained as average values for the period 2010–2014 (FAOSTAT, 2017c). $virtual\ nutrients\ imp_j$ presents a value of 0.85, 1.14 and 0.78 for N, $P_2O_5$ and $K_2O$, respectively. For $P_2O_5$ it is assumed a value of 1 indicating that all consumption comes from imports and there is no domestic production. The value of $virtual\ nutrients\ imp_j$ refers directly to one fertiliser, when there is only one nutrient per fertiliser (e.g., Ammonium Sulphate: 20-0-0). When more than one nutrient is present (e.g., NPK compound), $virtual\ nutrients\ imp_j$ is weighted based on the N, $P_2O_5$ and $K_2O$ content of the fertiliser (Table A1). Moreover, we assume that the production of fertilisers is homogeneous throughout the country and as a result the obtained ratio $virtual\ nutrients\ imp_j$ from national data is applicable at the catchment level.

Similarly, the virtual water ($m^3$) or embodied energy (J) *k* in virtual nutrients from domestic production ($virtual\ nutrients_{km\ domestic}$) is calculated as:

$$virtual\ nutrients_{ik\ domestic} = \sum fertiliser_{ijk} \times (1 - fert\ imp_j)) \tag{2}$$

For virtual water, Eqs. (1) and (2) are calculated independently for blue and green water. It is assumed that fertiliser consumption is positive and directly proportional with the amount of freshwater and energy consumed (Table A1). It is assumed that the production of fertilisers is homogeneous throughout the country and national level indicators are applicable at the catchment level. For non-processed food products from crops, i.e., potato and carrot, the calculated $virtual\ nutrients_{ik\ overseas}$ and $virtual\ nutrients_{ik\ domestic}$, refer directly to the food products under study. For food products processed from crops, $virtual\ nutrients_{ik\ overseas}$ and $virtual\ nutrients_{ik\ domestic}$ need to be converted from the crop to the food product (1 kg rapeseed oil = 5.47 kg rapeseed, 1 kg sugar = 5.56 kg sugar beet, 1 kg wheat flour = 1.15 kg wheat grain).

***Animal feed***

First the contribution of crop *m* required to produce compound feed for each animal product *l* (i.e., milk, cheese, beef, chicken and eggs) ($crop\ contribution_l$) is determined:

$$Crop\ \ contribution_l = \frac{weight\ crop_{lm}}{\sum weight\ crop_l} \tag{3}$$

Where, *weight crop*$_{lm}$: amount of crop *m* (kg) required to produce the compound feed for 1 kg animal product *l* or 1 egg, *Σ weight crop*$_l$: total amount of crops (kg) required to produce the compound feed for 1 kg animal product *l* or 1 egg.

The share of each crop *m* to produce compound feed is obtained from the process contribution table of each animal product *l* within SimaPro. Data are not made available because of license agreement conditions.

Afterwards the ratio of feed that is imported to produce domestic animal product *l* (*import animal feed*$_l$) is calculated as:

$$import\ feed_l = \Sigma \frac{import_m}{domestic\ supply_m} \times \frac{feed_m}{domestic\ supply_m} \times crop\ \ contribution_l \tag{4}$$

Where, *imports*$_m$: total UK imports of crops *m* (t); *domestic supply*$_m$: total UK domestic supply of crops *m* (t). *domestic supply*$_m$ equals to the sum of national production and imports, minus exports and changes in stock. Domestic supply includes *food*, *processing*, *feed*, *seed* and *other* classifications. *Feed m*: crops *m* allocated as animal feed within the domestic supply.

*imports*$_m$, *domestic supply*$_m$ and *feed*$_m$ are obtained from the 2013 Food Balance Sheet of crops primary equivalents (FAOSTAT, 2017b). Eq. (4) assumes that feed production is homogeneous throughout the country and that the use of a ratio obtained from national data is applicable at the catchment level. It is assumed that the share of feed category within domestic supply is the same as for imports. Eq. (4) is applied to calculate the imports from compound feed or maize silage (maize silage is only used in the dairy products i.e., milk and cheese). Since maize silage does not require processing with other crops, *crop contribution*$_l$ is not considered in Eq. (4) to estimate *import feed*$_l$. The ratio is not applied to pastures and grass silage as they are assumed to all come from domestic production.

The overseas virtual water (m$^3$) or embodied energy (J) *k* in feed (compound feed or maize silage) for each animal product *l* (*feed*$_{kl\ overseas}$) are calculated as:

$$feed_{kl\ \ overseas} = feed_{kl} \times imports\ feed\ _l \tag{5}$$

Where, *feed*$_{kl}$: virtual water (m$^3$) or embodied energy (J) *k* in feed in each animal product *l*.

Then the domestic virtual water (m$^3$) or embodied energy (J) *k* (*feed*$_{kl\ domestic}$) are calculated as:

$$feed_{kl\ \ domestic} = feed_{kl} \times (1 - imports\ feed\ _l) \tag{6}$$

For virtual water, Eqs. (5) and (6) are calculated independently for blue and green water.

### 2.2.2. The overseas and domestic virtual water and embodied energy consumption

Based on the food purchased per person in weight and calorific value (Table 1), the blue virtual water (m$^3$), green virtual water (m$^3$) and embodied energy (J) of each food product *l* can be calculated for the total population in the catchment. To estimate the food consumption that is imported from overseas a ratio is applied to each food product *n* (*ratio import*$_n$):

$$ratio\ import_n = \frac{imports_n}{domestic\ supply_n} \times \frac{(food\ \ supply_n + processing_n)}{domestic\ supply_n} \tag{7}$$

Where, *imports*$_n$: total UK imports for each food product *n* (t), *domestic supply*$_n$: total UK food domestic supply (t) for each product *n*. *domestic supply*$_n$ is defined the same as in Eq. (4), *food supply*$_n$: amount of the domestic supply for each product *n* that is allocated for directly human consumption (t), *processing*$_n$: amount of the domestic supply for each product *n* that undergoes some manufacturing process before being consumed (t).

Eq. (7) only accounts for the domestic supply exclusively allocated for human consumption. Food supply and processing categories are selected from 2013 Commodity Balance Sheet of crops and livestock primary equivalents (FAOSTAT, 2017b) as those that exclusively relate to human consumption, whereas classifications such as feed and seed are not considered in the ratio. *Ratio import*$_n$ assumes that food production is homogeneous throughout the country, similar as in Eqs. (1) and (4), and that the use of a ratio obtained from national data is applicable for the Tamar catchment. Moreover, it is assumed that the share of food supply and processing categories within domestic supply is the same as for imports. *ratio import*$_n$ for rice is larger than 1, but it is assumed the value is equal to 1, meaning that all the consumption is maintained by imports.

An additional ratio is created to represent the share of each UK trade partner *p* in the imports of each food product *n* (*ratio country import*$_{np}$):

$$ratio\ country\ import_{np} = \frac{imports_{np}}{\sum imports_n} \tag{8}$$

For this ratio, the value of imports ($) is used because several commodities (e.g., vegetables fresh, vegetables frozen and vegetables in vinegar) are grouped in one classification (i.e., vegetables). The trade data have been corrected by tracing the origins of the traded products, following Scherer and Pfister (2016) instead of applying a multi-regional input-output approach. This correction has been made for those countries that export some food products, but do not actually produce them according to food production statistics for the year 2013 (FAOSTAT, 2017d). For those non-producing countries, a factor of import shares from the exporting countries by food product is applied. Only countries that contribute to more than 5% of the total imports by food product are included. Table A2 in the Supplementary material shows the import countries considered by food product. Data are obtained from the 2013 Detailed Trade Matrix (FAOSTAT, 2017c).

Finally, the consumption of virtual water (m$^3$) or embodied energy (J) flows *k* for each food product *n* from overseas (*flows*$_{knp\ overseas}$, in m$^3$ or J) per UK trade partner *p* and domestically (*flows*$_{knp\ domestic}$, in m$^3$ or J) are calculated as:

$$flows\ _{knp\ overseas} = flows_{kn} \times ratio\ import_n \times ratio\ country\ import_n \tag{9}$$

$$flows_{kn\ domestic} = flows_{kn} - \sum flows_{knp\ overseas} \tag{10}$$

Where, *flows*$_{kn}$: virtual water (m$^3$) or embodied energy (J) flows *k* for each food product *n*.

For virtual water, Eqs. (9) and (10) are calculated independently for blue and green water. Blue water and green water flows for crop products are updated for each trade partner import based on Mekonnen and Hoekstra (2010a,b). Origin of imported water is not considered in crops for the production of feed.

## 3. Results

### 3.1. Virtual water and embodied energy for each food product and the catchment

Considering the existing diet and products selected, the Tamar catchment consumes annually about 834 TJ, 17 hm$^3$ and 244 hm$^3$ of energy, blue water and green water, respectively. These values include resources consumed directly within the catchment and indirectly elsewhere. Chicken, beef and milk are the products which consume most of the energy, accounting for 31% (258 TJ), 30% (250 TJ) and 12% (98 TJ) of the total embodied energy in food, respectively. Regarding water, rice accounts for 74% (12.4 hm$^3$) of the total blue water consumption, followed by beef with 11% (1.8 hm$^3$). Beef and milk show the largest appropriation of green water with 60% (146 hm$^3$) and 14% (34 hm$^3$), respectively, due to the role that pastures play on animal feed for ruminant livestock systems (Fig. 2 and Table A3 in the Supplemental material).

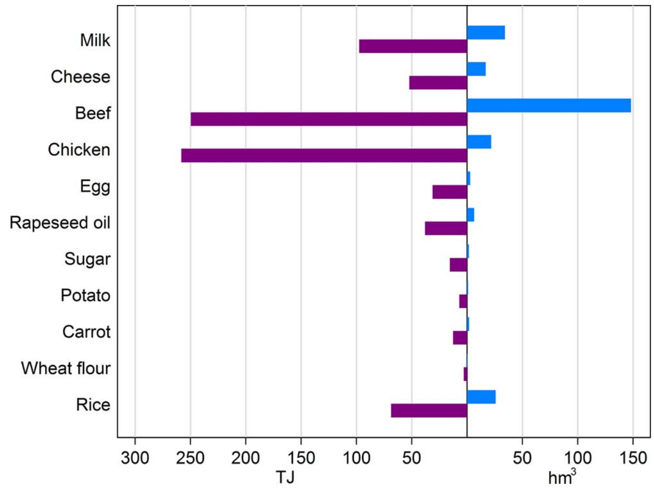


**Fig. 2.** Embodied energy (TJ) and virtual water (blue water + green water, $hm^3$) for food purchase in the Tamar catchment according to an average diet and food products selection.

**Table 2**
Virtual water (L) and embodied energy (KJ) per kcal of food product.

| Product | Blue water | Green water | Energy |
|---|---|---|---|
| Milk | 0.025 | 2.6 | 7.6 |
| Cheese | 0.025 | 2.6 | 8.3 |
| Beef | 0.376 | 30.4 | 51.8 |
| Chicken | 0.055 | 1.7 | 20.8 |
| Egg | 0.055 | 1.2 | 14.5 |
| Rapeseed oil | 0.007 | 0.3 | 1.8 |
| Sugar | 0.007 | 0.2 | 1.8 |
| Potato | 0.024 | 0.1 | 1.0 |
| Carrot | 0.137 | 0.1 | 1.9 |
| Wheat flour | 0.004 | 0.1 | 1.0 |
| Rice | 1.169 | 1.3 | 6.5 |

Beef stands as the food product with the largest embodied energy per calorific value (51.8 KJ/kcal), followed by chicken (20.8 KJ/kcal) and egg (14.5 KJ/kcal). Rice is the product that demands most blue water with 1.17 L/kcal, whereas for green water demand for beef reaches a value of 30.4 L/kcal (Table 2). As a result, dietary preferences and the resource embedded per calorific value determine the final water and energy demand in the catchment (See Table A4 for virtual water and embodied energy per kg of food product).

### 3.2. The relevance of imports to meet food demands

In this study, in order to meet the food demand in the catchment a distinction is made between the imports required as: 1) inputs to domestic food production (i.e., virtual nutrients and animal feed, excluding pastures); and 2) food imports. Considering both forms of imports, the catchment imports 423 TJ energy, 15 $hm^3$ blue water and 109 $hm^3$ green water, i.e., 51%, 88% and 45% of the total embodied energy, blue virtual water and green virtual water in food consumed (see Figs. 3 and A2).

Imports of animal feed and virtual nutrients to maintain domestic production are noticeable in terms of energy demand, with 49 TJ and 10 TJ, respectively (Figs. 3 and A2). Chicken is the food product with the largest use of imported animal feed (22.4 TJ), followed by beef (11.2 TJ) and milk (10.7 TJ). This is because chicken production relies more on processed feed in comparison with other animal products. Green water (5.9 $hm^3$) is also found in imported feed (Figs. 3 and A2), which is linked with the required use of land to produce crops such as barley, oat, wheat, soybean and maize. Imports of virtual nutrients to produce domestic crops do not represent a significant amount of the total virtual water. Virtual nutrients are key for some products such as potato, rapeseed oil and wheat flour production, comprising 34% (2.2 TJ), 18% (6.6 TJ) and 15% (0.4 TJ) of their total embodied energy (Fig. 3 and Table A5). Those embodied energy values of virtual nutrients imports have a similar magnitude as the total embodied energy of imports of potato (2.3 TJ), rapeseed oil (7.1 TJ) and wheat flour (0.4 TJ). There are two main reasons for the relatively larger values of water and energy resulted from virtual nutrients for rapeseed oil. Firstly, rapeseed is a processed product and about 5.47 kg of rapeseed are required for the production of 1 kg rapeseed oil. Secondly, according to the diet intake of food products considered, rapeseed oil (the product chosen to represent fats) accounts for 12% of the daily calorie intake in comparison with 4%, 4% and 2% for potatoes, carrots and wheat flour, respectively.

Imported food products represent the largest fraction of the total embodied energy and virtual water with 44% energy (364 TJ), 88% blue water (14.9 $hm^3$) and 42% green water (103 $hm^3$) of the total. The products with considerable virtual water and embodied energy in direct food imports are: a) carrot, rapeseed oil, rice, sugar and wheat flour with > 90% blue virtual water, b) carrot, cheese, rice and sugar with > 60% green virtual water and embodied energy (Fig. 3 and Table A5).

Fig. 4 shows the virtual water and embodied energy, identifying the main processes required to produce each product. In this case imported compound feed and virtual nutrients for domestic production and compound feed and virtual nutrients used elsewhere to produce food imports are grouped together under the imports category. Compound feed production is the process with the largest energy demand (342 TJ in total), which reaches 485 TJ when including pastures to provide animal feed. Animal feed (including pastures) consumes about 58% of the total energy and 48% of this energy come from imports. Chicken is responsible for the demand of about 50% of the total compound feed production process and accounts for 170 TJ (88 TJ in imports and 82 TJ from domestic production). In comparison to chicken, beef requires less energy for compound feed production (39 TJ in imports and 33 TJ from local production), because pastures are also used for feed (43 TJ in imports and 68 TJ from local production). To meet crop water needs, 36 $hm^3$ green water is required for compound feed production (19 $hm^3$ in imports and 17 $hm^3$ from local production). When considering green water consumption for pasture production (183 $hm^3$), animal feed accounts for 90% of the total green water consumption. With 146 $hm^3$ of green virtual water, beef is the food product that depends significantly on this water source (58 $hm^3$ in imports and 88 $hm^3$ from local production). Regarding blue water, 92% (15.5 $hm^3$) is used for meeting crop water requirements i.e., irrigation purposes (14.4 $hm^3$ in imports and 1.2 $hm^3$ from local production), with rice being the most demanding food product (12.4 $hm^3$) (see Tables A6 and A7 in Supplemental material for more details). Irrigation is the process that demands the largest amount of energy for the crop-based products, with 38% of their total energy demand (145 TJ), followed by fertilisers production amounting 24% (35 TJ).

The catchment is importing virtual water and embodied energy from 21 countries when considering only those countries that contribute to more than 5% of the total imports by food product. Europe is the region where most of the imports are coming from, representing 86% (313 TJ), 44% (7 $hm^3$) and 88% (91 $hm^3$) of the embodied energy, blue virtual water and green virtual water in food imports, respectively. Countries in South Asia, including Pakistan, India and Thailand are also key UK trade partners, accounting for 12% energy, 55% blue water and 11% green water (see Fig. 5). In terms of calorific value, Europe is providing 76% of the total demand, whereas South Asia and the remaining countries 17% and 8% (Table A8 in Supplementary material).

Ireland (125.2 TJ), The Netherlands (73.2 TJ), Spain (27 TJ), Pakistan (24.5 TJ) and Poland (22.7 TJ) are the countries providing the largest amounts of energy (see Fig. 5). In contrast, blue water mainly comes from Pakistan (5.4 $hm^3$), Spain (4.2 $hm^3$) and India (2.1 $hm^3$).

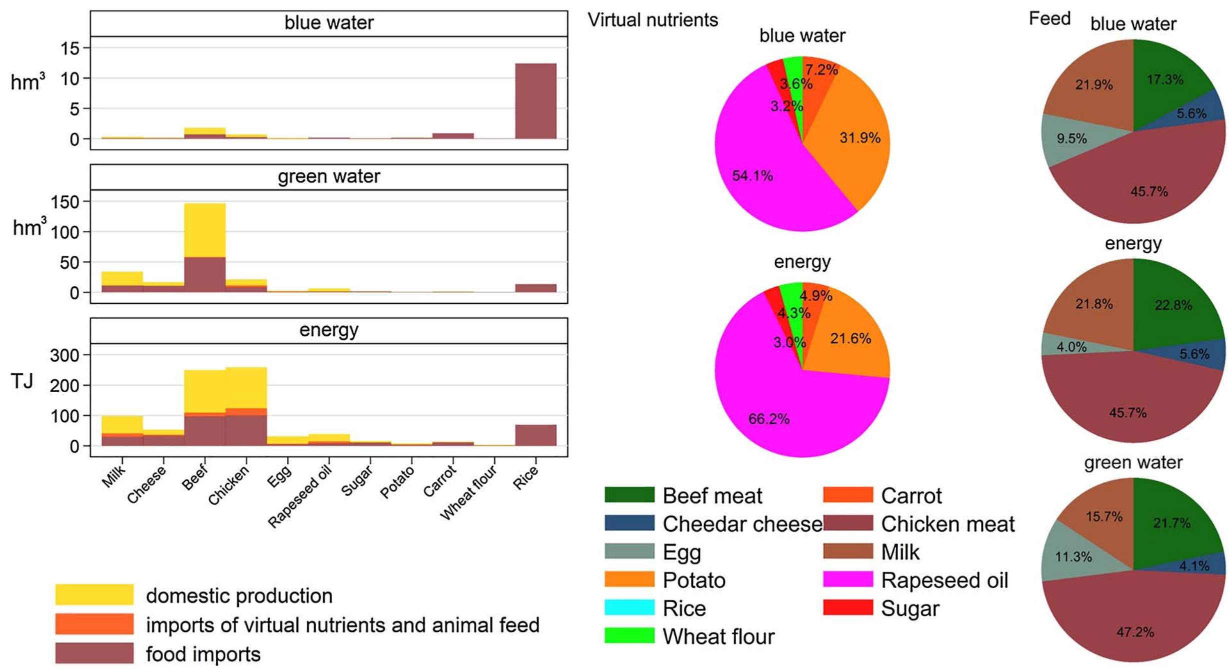


**Fig. 3.** Total blue virtual water (hm$^3$), green virtual water (hm$^3$) and embodied energy (TJ) in the selected food products consumed in the catchment, differentiating domestic resources and those embedded in imported food products, virtual nutrients and animal feed (graph bar). Blue virtual water (m$^3$), green virtual water (hm$^3$) and embodied energy (TJ) by food product and distinguishing virtual nutrients and animal feed (pie charts). Animal feed includes compound feed and maize silage, but not pastures as they are assumed to be grown locally for domestic food production.

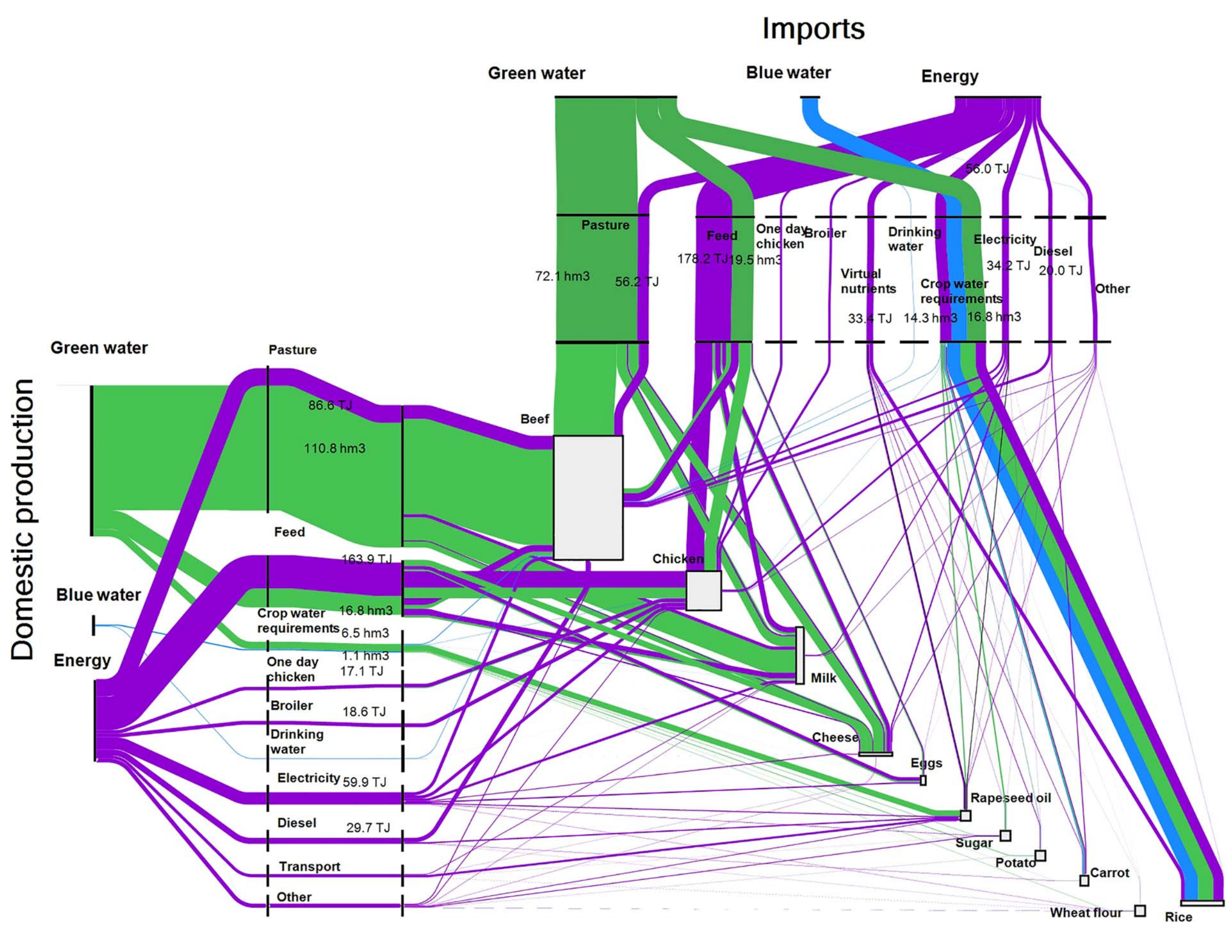


**Fig. 4.** Total embodied energy (TJ), blue virtual water (hm$^3$) and green virtual water (hm$^3$) flows by main processes required to produce the selected products, differentiating domestic resources and imports. Processes that contribute to < 2% per food product and < 1% per process of the total energy, blue water or green water are grouped into the 'Other' classification. 'Pasture' includes both grazed grass in pasture and grass silage. Details of the values behind the flows are presented in A7 in Supplemental material.

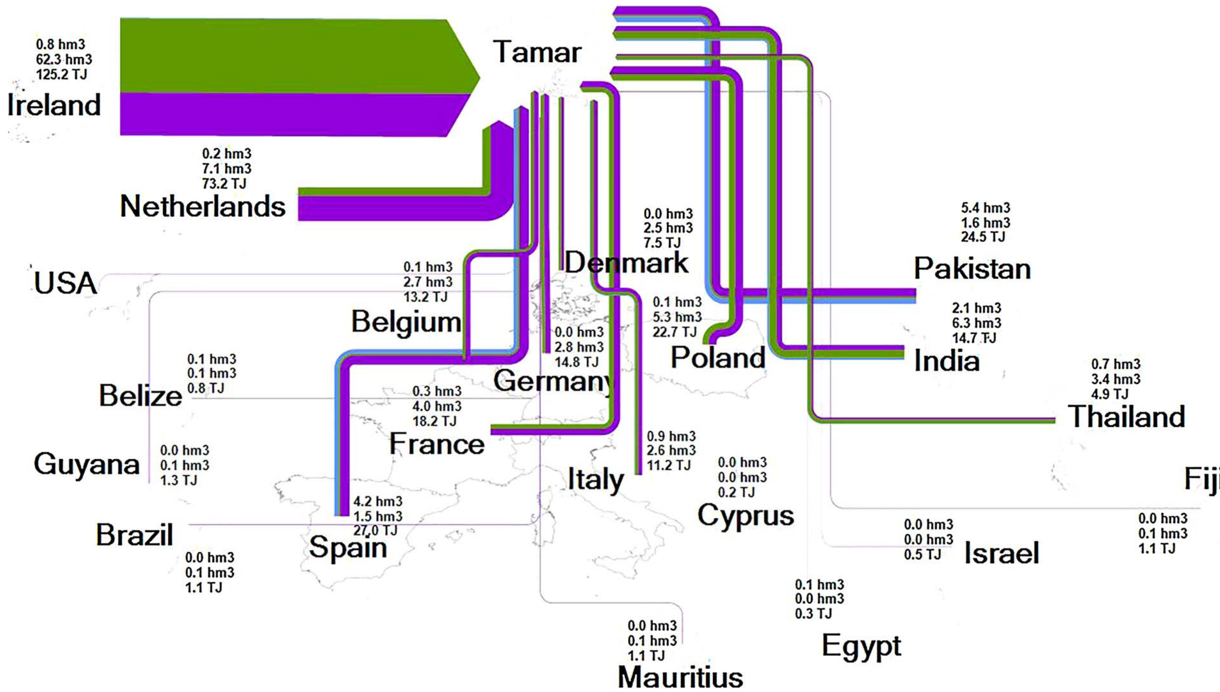


**Fig. 5.** Blue virtual water ($hm^3$), green virtual water ($hm^3$) and embodied energy (TJ) for food imports by main UK trade partners.

Green water use is mostly in Ireland (62.3 $hm^3$). Ireland is the main provider of beef (88.6 TJ energy, 0.6 $hm^3$ blue water and 52.8 $hm^3$ green water), whereas chicken is mostly supplied by The Netherlands (63 TJ energy, 0.17 $hm^3$ blue water and 5.2 $hm^3$ green water) and Poland (15.8 TJ energy, 0.04 $hm^3$ blue water and 1.3 $hm^3$ green water). Most of the blue water imported is due to rice (Pakistan 5.9 $hm^3$, Spain 3.4 $hm^3$, India 2.1 $hm^3$ and Italy 0.9 $hm^3$) and carrots (Spain 0.9 $hm^3$) (see Figs. A4 –A6).

## 4. Discussion

### 4.1. The Tamar food purchase in a broader context

Our study has assessed the virtual water and embodied energy of selected food products consumed in the Tamar catchment, covering both products produced domestically and imported from other regions of the world. The results show that the catchment depends significantly on overseas imported food products for direct consumption, as well as on feed and virtual nutrients imports to maintain local production. Considering both sources of imports and existing dietary patterns, the catchment imports from outside the UK 423 TJ energy, 15 $hm^3$ blue water and 109 $hm^3$ green water (i.e., 51%, 88% and 45% of the total embodied energy, blue virtual water and green virtual water). Countries supplying the food requirements are mostly located in the EU (e.g., Ireland, The Netherlands, Spain and Germany), though the role of countries from South Asia, including Pakistan, India and Thailand, is also important. Unexpected shifts in these patterns can occur due to future changes on regulations and trade agreements following the UK's decision to leave the EU.

Approximately 88% of Tamar's blue virtual water in food is supplied by imports. This suggests that avoiding using domestic resources relies on the generation of environmental externalities in other regions. Consumption of the same amount of water or energy can have uneven environmental impacts depending on local conditions. For instance, half of UK's water footprint is located in places including Pakistan, Spain and India where blue water consumption exceeds maximum sustainable thresholds (Hoekstra and Mekonnen, 2016). Tamar might be considered to be secure in terms of water availability, but it can still face water and food security challenges if food trade shocks take place because of, for example, climate change impacts along the food supply chain. In fact, the country has already been identified as one of the most vulnerable to food production crises occurring elsewhere and propagating in the global trade network (Tamea et al., 2016). Some strategies that have been discussed to mitigate imported UK water-food risks include higher food self-sufficiency and diversification of imports of water-intensive commodities favouring the sourcing from water-abundant regions (Hoekstra and Mekonnen, 2016).

In our study, approximately 92% of total blue water for food is due to irrigation (i.e., from 43% for milk and cheese to 100% for rice). The remaining 8% is allocated to other processes including animal drinking water, cleaning activities, production of electricity and fertiliser production (see Table A7 for more details). Although rare in Tamar, irrigation has been used in the UK to cope with droughts in the past (Wreford and Adger, 2010) and might be needed in the future due to the expected changing climate conditions (Rey et al., 2016). Implementation of additional irrigation practices will not only lead to pressures on local water resources but also an increase in energy consumption and associated energy costs for farmers.

### 4.2. The environmental implications of virtual water and embodied energy in diets

Diets in our society are currently shaping the demand for key natural resources such as water, land and energy (Busscher, 2012; Nijdam et al., 2012). Our study shows the dominant role of animal products (including beef, chicken, milk, cheese and eggs) on energy and freshwater consumption. According to existing diet and food commodities choices, animal products provide 40% of total calories in the Tamar catchment and are responsible for 87% of energy, 93% of green water and 19% of blue water consumed.

Total energy consumption per kcal of the selected animal products in our study follow the decreasing order: beef (51.8 KJ/kcal) > chicken (20.8 KJ/kcal) > eggs (14.5 KJ/kcal) > cheese (8.3 KJ/kcal) > milk (7.6 KJ/kcal). These different values are related to different feed-to-food conversion ratios (Eshel et al., 2014). For instance, approximately 38 kcal of feed energy content is need to produce 1 kcal of beef for human consumption, whereas for dairy this value is 7 kcal of feed (Eshel et al., 2014). Overall, the environmental impacts associated with livestock products mainly arise from feed provision (Pelletier, 2008; Boggia et al., 2010; Leinonen et al., 2012; Kebreab et al., 2016; Tallentire et al., 2017). For the selected animal products in our study, 90% of the green water and 58% of the energy are used to produce animal feed, including pastures.

Animal products also consume significant amounts of green water, which is related ultimately with the appropriation of land for grazing and production of crops for animal feed. Pastureland or cropland production has several environmental implications, including biodiversity losses and changes on available blue water resources, which can occur depending on the types of land use changes and management practices (Deutsch et al., 2010). Beef requires the largest volume of green water per kcal (30.4 L/kcal) and land, but the type of land used is mainly grasslands, which might not have other alternative use than grazing. In contrast, monogastric species such as poultry require lower amount of green water (1.7 L/kcal) and land, but they rely on feeds from highly productive cropland. It might appear that poultry is more efficient in terms of freshwater and energy consumption than beef (Table 2). However, there is still a lack of understanding of the trade-offs between increasing the efficiency of livestock production through crop-based feeds and the pressure this creates through intensification and expansion of the world's croplands (Ridoutt et al., 2014).

Shifts towards diets with lower consumption of animal products represent the best option to increase production under limiting resources such as land (Erb et al., 2016) and water, while energy consumption and related GHG impacts can also be reduced (Tilman and Clark, 2014; Hallström et al., 2015; Tom et al., 2016). Food purchase in the UK is not yet associated with sustainability goals and is recommended to relate cooking practices and meanings of food (e.g., healthiness, localness) to facilitate effective changes on food habits (O'Keefe et al., 2016). Information on a set of indicators in relation to environmental impacts of food products, including, e.g., level of water sustainable practices in the country of production (e.g., meeting water flow requirements and aquifer recharge), life cycle GHG emissions per kcal of the product and GHG in food miles vs GHG in supermarket trips by car, could help consumers to make more environmental sustainable choices and relate them to the meaning of food. To help achieve this, actors along the whole food supply chain, from farmers, food manufacturers, through to retailers, will need to commit to more transparency on the practices involved along the suuply chain to better evaluate and promote more sustainable practices from a systems perspective.

### *4.3. Areas of improvement in LCA on water-energy-food nexus studies*

Coherent understanding of key links of required resources for maintaining human activities, and from a life cycle perspective, can allow exploitation of opportunities for more integrated resource management. Existing LCA databases such as Agri-footprint, ecoinvent or AGRIBALYSE can be used as a starting point for mapping critical flows, e.g., of water and energy for provision of food. Those databases provide details of technological processes, as well as required materials and energy inputs to produce a wide range of products. But geographical and temporal information is still limited and there is a strong dependence on global, regional or national average values. This makes it difficult to follow a spatially explicit evaluation and can lead to non-contextualised assessments for the purposes of convenience and simplicity (Fang et al., 2015; Paterson et al., 2015). Although the established LCA methodology is aspatial and static in nature, spatially explicit and dynamical LCA methods are currently being developed (Maier et al., 2017) and could be available in the near future for FEW studies.

In LCA studies there has also been a tendency to focus on energy and GHG, while water seems to have traditionally been overlooked. Blue water is already specified in databases such as ecoinvent and GaBi. However, the water from rainfall source used by plants in the area where it falls (i.e., green water) is still not considered in those databases. Even the ISO Standard 14046 for water footprinting (ISO, 2014) does not take into account green water, which has now been recognised as a key input during life cycle inventory for water use assessments (FAO, under elaboration). The improvement from our study is to add green water consumption to the datasets readily available in the Agri-footprint database, recognising the key role that green water plays in food provision and its linkages with existing land uses.

LCA alone will not be sufficient to address FEW nexus evaluations for geographical areas because of the difficulty to account for all sectors and activities within an area. As Eshel et al. (2014) also points out, LCA studies are still too few and too local to adequately address production diversity (e.g., food system). This is a barrier to LCA becoming scalable. An alternative option is the use of hybrid LCA, which links national input-output (IO) analysis (i.e., a top-down approach) and process-based life cycle inventory (i.e., a bottom-up approach). Hybrid LCA can apply coefficients to provide multipliers for imported products that are not produced domestically and thus not represented adequately in the national IO tables. For instance, Virtanen et al. (2011) derived a hybrid LCA model from economic IO tables of the Finnish national economy associated with environmental emissions and characterisation data to compute the environmental impacts. Hybrid LCA methods have already been applied to evaluate the energy consumption and GHG emissions of the Mediterranean diet (Pairotti et al., 2015) and the energy and water nexus in Chinese electricity production (Feng et al., 2014), among others.

### *4.4. Limitations of our research*

Due to data availability, our study did not include the entire range of food products purchased at home in Tamar. Some important food categories such as fruits, bread and fish were not considered or products within a same food category (e.g., vegetable vs. animal fats) were not distinguished. Future updates of the Agri-footprint database could allow the analysis to be extended to additional food products. Moreover, our study does not use food products from different LCI databases because of the varying assumptions, system boundaries and data quality, which Cucurachi et al. (2016) identified as a limitation for the use of several LCI databases in meta-analysis. Between the most known LCI databases for food products (Agri-footprint, ecoinvent and AGRYBALASE) Corrado et al. (2017) also highlighted that there are different assumptions, including system boundaries and agricultural and irrigation modelling, making it difficult to directly compare outputs between those databases.

Irrigation and green water embedded in crops depends on local climatic and soil conditions, which differ spatially and temporally. We have attempted to address the spatial variability with the inclusion of green and blue water based on crop water requirements from each importing country. Nevertheless, even within a country crop production changes spatially and temporally, leading to heterogeneous levels of crop water requirements and as a result of irrigated demand (Finger, 2013).

In our study imports from other UK regions is not considered. Only the domestic production versus the overseas imports is distinguished with the ratios used to estimate the proportions of food, virtual nutrients and compound feed. As a result, consumption of resources and food from domestic production cover the Tamar but other UK regions too. Availability of intra-national trade data would help to resolve this constraint. It is also assumed that within the national domestic supply (i.e., food, processing, feed, seed and others classifications) the shares of food supply and processing or feed categories are the same as those for imports. Moreover, some food classifications in the FAO Food Balance Sheets include crops and their derivatives (e.g., 'wheat and products', 'maize and products') instead of only values on domestic supply of crops. It has been assumed that within national domestic supply the shares of crops and their derivatives are equal. Those assumptions do not allow the consideration of the different weights that some food products or crops could have within distinct categories of the national domestic supply.

Finally, the transportation of food from the origin of production (i.e., farm for a primary product or factory for a processed product) to consumers – known as food miles – has not been entirely accounted for in the LCI datasets, which could change the energy and water results. There is no simple answer to the local vs. import issue for food, as local production does not necessarily mean environmental advantages over imports given that transport modes are found to be more important than transport distance (e.g., impacts per t-km increase in the following order for different transport modes: freight ship < rail < road < air freight) (Nemecek et al., 2016).

## 5. Conclusions

This paper presents a comprehensive accounting of the virtual water (blue and green) and embodied energy in food products consumed in the Tamar catchment in South West England. Directly and indirectly, domestic food consumption in the catchment demands annually 834 TJ, 17 $hm^3$ and 244 $hm^3$ of energy, blue water and green water, respectively. Our study highlights the role of animal products for green water and energy consumption, including the required resources to provide feed and virtual nutrients. The Tamar is not self-sufficient in terms of food and requires imports of food products, as well as inputs such as virtual nutrients and animal feed for their local production, with 51%, 88% and 45% of the total embodied energy, blue virtual water and green virtual water coming from imports. In terms of key processes, animal feed production is the most significant, accounting for 58% and 90% of the total energy and green water demand. 92% of blue water is used for irrigation and primarily happens elsewhere due to imports. Irrigation demands the largest amount of energy for the crop-based products, with 38% of their total energy demand, followed by virtual nutrients amounting 24%.

This study is a first attempt to map the physical FEW linkages in Tamar and reveal the water and energy hotspots for food using LCA. Currently available databases, software and ongoing developments make LCA a key tool for FEW nexus assessments. A step forward on this research will be to link the approach in this study with FEW consumption data generated at a household level to evaluate the relevant FEW practices at home (Farr-Wharton and Comber, under elaboration).

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2018.01.018.

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