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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).