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Water Footprint and Life Cycle Assessment as approaches to assess potential impacts of products on water consumption. Key learning points from pilot studies on tea and margarine

Donna Jefferies [a,*], Ivan Muñoz [a], Juliet Hodges [a], Vanessa J. King [b], Maite Aldaya [c], Ali Ertug Ercin [c], Llorenç Milà i Canals [a], Arjen Y. Hoekstra [c]

[a] *Unilever, Safety & Environmental Assurance Centre, Colworth Science Park, Sharnbrook, Bedfordshire, MK44 1LQ, UK*
[b] *Unilever, Sustainable Sourcing Development Team, Colworth Science Park, Sharnbrook, Bedfordshire, MK44 1LQ, UK*
[c] *Twente Water Centre, University of Twente, P.O. Box 177, 7500 AE Enschede, The Netherlands*

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ABSTRACT

Water accounting and environmental impact assessment across the product's life cycle is gaining prominence. This paper presents two case studies of applying the Life Cycle Assessment (LCA) and Water Footprint (WF) approaches to tea and margarine. The WF, excluding grey water, of a carton of 50 g tea is 294 L green water and 10 L blue water, and that of a 500 g tub of margarine is 553 L green water, 109 L blue water. The inventory results in the LCA studies (blue water) are 13 L for tea and 114 L for margarine. In the impact assessment phase of WF, Coonoor in Southern India appears as a potential hotspot for tea production, although the water consumed in energy to boil the kettle and by the consumer are also significant. For margarine the main potential hotspot is irrigated sunflower around Zaporizhia in Ukraine. The impact assessment results of LCA for tea causes the water in the consumer use phase to be down-weighted and stresses the contribution from Coonoor due to the higher water scarcity of this region. Similarly the LCA impact assessment of margarine causes the palm oil contribution to be down-weighted due to the low water scarcity of Medan in Indonesia. From these case studies we identify similarities, differences and synergies at both the water accounting and impact assessment levels for both approaches with the purpose of improving and advancing the water resource assessment process.

1. Introduction

Freshwater in sufficient quantities and adequate quality is a fundamental resource to all ecological and societal activities, including food production, industrial activities, and human sanitary conditions. One of the biggest water problems around the world is scarcity. Currently, about one third of the world's population is threatened by a lack of freshwater to meet their daily needs (IWMI, 2007), and yet increased water scarcity is expected in the future in many regions, due to a variety of factors such as population growth, pollution of existing resources, climate change, urbanization and changing lifestyles. In many regions, water supplies are not sufficient to satisfy all agricultural, industrial and environmental demands.

Given that severe freshwater scarcity is a common phenomenon in many regions of the world, improving the governance of the world's limited annual freshwater supply is a major challenge, not only relevant to water users and managers but also to final consumers, businesses and policymakers in a more general sense. About 86% of all water used in the world is to grow food. Therefore, the need for the food industry to take a responsible approach towards the sustainable use and conservation of freshwater is vital. However, collecting and disseminating meaningful water-related information is a complicated and difficult undertaking, since corporate water accounting methods are still under development and require further refinement (Morrison et al., 2010). It seems nevertheless agreed that methods aiming to measure impacts on water consumption from consumer products must take a supply-chain or life-cycle perspective, due to the majority of burden on water resources being indirect (Morrison et al., 2010). There are currently two main approaches enabling such a comprehensive assessment of products, namely Water Footprint (WF) and Life Cycle Assessment (LCA).

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[*] Corresponding author. Tel.: +44 (0) 1234 264880; fax: +44 (0) 1234 264744.
E-mail address: donna.jefferies@unilever.com (D. Jefferies).

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The WF concept was introduced by Hoekstra in 2002 (Hoekstra, 2003), and subsequently elaborated by Chapagain and Hoekstra (2004) as an indicator of human appropriation of freshwater resources that incorporates both direct and indirect water use of a consumer or producer. This method has a wide applicability; it is possible to derive the WF of an individual, a community, a business or a nation. In the particular case of products, the WF is the total volume of freshwater used to produce the product, summed over the various steps of the production chain. WF is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total water footprint are specified geographically and temporally (Hoekstra et al., 2009a). The blue water footprint refers to consumption of blue water resources (surface and ground water) along the supply chain of a product. ‘Consumption’ refers to loss of water from the available ground-surface water body in a catchment area, which happens when water evaporates, is incorporated into a product or returns to another catchment area or the sea (Hoekstra et al., 2011). The green water footprint refers to consumption of green water resources (rainwater stored in the soil as soil moisture). The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.

LCA is a tool to measure the various environmental impacts caused by products from cradle to grave (Finnveden et al., 2009). However, in most LCA studies water consumption has been traditionally omitted (Milà i Canals et al., 2009). Nevertheless, through the UNEP/SETAC Life Cycle Initiative and ISO, the LCA community has started pushing the development of comprehensive methods for water accounting at both the inventory and impact assessment levels. In a recent paper, Berger and Finkbeiner (2010) reviewed thirteen different methods enabling the assessment of water use impacts in LCA.

One of the main purposes of both LCA and WF is the identification of so-called ‘hot-spots’. This commonly refers to identifying activities within the life cycle of a product or service that have a significant contribution to the total potential impact attributed to the product. This means identifying regions where the water footprint of the product is large and water scarcity is high too. This paper presents a practical comparison of these two approaches, illustrated using pilot studies on tea and margarine. These studies were conducted in order to quantify water consumption associated with these products and to understand their potential impact on water scarcity taking a life cycle perspective. In addition, the general goal of this work was to explore strengths and weaknesses of both approaches and to identify areas where the LCA and WF communities might learn from one another. We sought to apply the methodologies as they were applied at the time (2010), and where relevant we discuss how both approaches have moved on since the pilot.

2. Data, methods and assumptions

2.1. Products under study

The case study on tea was based on a specific pack of 25 Tea Bags, which includes 50 g tea. The tea for the product is grown in Kenya, Indonesia and India (specific locations in Table 1). Dry tea leaves are transported to Manchester in the UK, where they are blended and sent for packing in Brussels, from where the product is distributed. It is assumed that consumption of the product occurs in Belgium.

The case study on margarine was based on a specific 500 g tub of margarine, produced in Pratau (Germany) and sold in the German market. The main ingredients for margarine production are several vegetable oils produced in several countries (locations in Table 1). Fig. 1 shows a simplified diagram of the products’ life cycles.

2.2. Water Footprint

The WF of products was calculated following the methodology described in Hoekstra et al. (2009a) and Ercin et al. (2010). However, grey water was excluded from this work, with the focus on only green and blue water footprints. Water quality is currently addressed separately from quantity within Unilever, and the LCA models addressing various potential impacts on water quality (e.g. eutrophication, acidification, aquatic eco-toxicity) were outside scope of this work and therefore grey water was also excluded.

Both operational and supply-chain water footprint consist of two parts: the water footprint that can be directly related to inputs applied in or for the production of our product and an overhead water footprint. The overhead water footprint refers to freshwater use that in first instance cannot be fully associated with the production of the specific product considered, but refers to freshwater use that associates with supporting activities and materials used in the business, which produces not just this specific product but other products as well.

2.2.1. Supply chain WF

The supply-chain water footprint is defined as the amount of freshwater consumed to produce all the goods and services that form the input of production at the specific business unit. In the scope of this study, the ingredients (tea, rapeseed oil etc.) and other components (packing materials, labelling materials etc.) are included in the supply chain water footprint calculations.

The green and blue water footprints of the agricultural ingredients (tea, rapeseed oil, maize oil, sunflower oil, palm oil) are calculated using the methodology described in Hoekstra et al. (2009a). The green and blue water evapotranspiration were estimated using the CROPWAT model (FAO, 2003). Within the CROPWAT model, the ‘irrigation schedule option’ was applied, which includes a dynamic soil water balance and keeps track of the soil moisture content over time. The calculations are done using climate data from the nearest and most representative meteorological stations located in the major crop-producing regions obtained from the CLIMWAT database (FAO, 2006) and a specific cropping pattern for each crop according to the type of climate.

For tea, actual irrigation data averaged over several years was available. These water volumes, which referred to water abstraction, were lower than the theoretical evapotranspiration requirement, and were used in preference.

Yields (tonne/ha) were obtained where possible from suppliers, and the remainder were taken from FAO (2009a), using averages over 2005–2007. It must be highlighted that there was a lack of specific sourcing information for crops in the margarine study, since only the country of origin was known, but not the region within a country. Therefore regions had to be assumed based on general information on crop growing regions, for example Monfreda et al. (2008) and the United States Division of Agriculture (USDA, 2004).

Water consumed during processing of raw materials involves blue water consumption, especially in edible oils production. Inventory data from a recent LCA study on margarine provided data from oil mills on water abstraction (Nilsson et al., 2010). It was assumed that water used in the mills for steam production is not consumed, as it is basically used in a closed system. With regard to cooling water, it was assumed that only 5% of the abstracted water is consumed (evaporated), whereas the remaining 95% is discharged again to the environment (Rosiek et al., 2010; Muñoz et al., 2010).

Table 1
Summary of data used in calculating the supply chain water footprints of tea and margarine.

Item	Raw material	Location[a]	Water footprint of raw material (m^3 tonne^{-1})		Water footprint of raw material processing (m^3 tonne^{-1})		Product fraction	Value fraction	Water footprint of item (m^3 tonne^{-1})		Data sources
			Green	Blue	Green	Blue			Green	Blue	
Black tea	Fresh tea leaves	Kericho plantation (Kenya)	880	0	0	0.03	0.26	1	3394	0.12	Crop requirements calculated with CROPWAT, with crop coefficients from Allen et al. (1998), Chapagain and Hoekstra (2004) and Salimi and Mir Latif (2008). On-farm processing based on data from suppliers and assuming that 10% of abstracted water by factories is consumed (evaporated).
		Kericho smallholders (Kenya)	1453	0	0	0.03	0.26	1	5605	0.12	
		Nyeri (Kenya)	930	0	0	0.03	0.26	1	3589	0.12	
		Agrabinta (Indonesia)	2214	0	0	0.03	0.26	1	8540	0.12	
		Kotagiri and Coonor (India)	1015	202	0	0.03	0.26	1	4968	777	
Rapeseed oil	Rapeseed	Salzgitter (Germany)	278	0	0	0.5	0.38	0.77	560	1.0	Crop requirements calculated with CROPWAT, with crop coefficients from Allen et al. (1998) and Chapagain and Hoekstra (2004). Processing based on (Nilsson et al., 2010)
		Chojna (Poland)	251	0	0	0.5	0.38	0.77	506	1.0	
		Karlovy Vary (Czech Republic)	201	0	0	0.5	0.38	0.77	405	1.0	
Maize oil	Maize	Szederkeny (Hungary)	302	398	0	0.5	0.03	0.06	1400	797	
		Alsace (France)	246	130	0	0.5	0.03	0.06	752	261	
Sunflower oil	Sunflower seeds	Tres Arroyos (Argentina)	1739	1925	0	0.5	0.38	0.82	7860	4131	
		Zaporizhia (Ukraine)	1501	2242	0	0.5	0.38	0.82	8030	4811	
Interesterified fat of palm kernel oil and palm oil	Oil palm fruit	Pratau (Germany), Palm fruit from Indonesia	714	27	0	2.9	0.24	1.00	3025	122	
Tea bag, tag, envelope	Kraft paper, unbleached	Undefined	785	0	0	11.5	1	1	785	11.5	Green water calculated based on 369 m^3 per tonne wood (Gerbens-Leenes et al., 2008) and wood requirements per tonne material according to the ecoinvent database: 2.13 tonnes wood per tonne kraft paper unbleached, 0.08 tonnes wood per tonne cellulose fibre, 2.07 tonnes wood per tonne solid bleached board, 0.24 tonnes wood per tonne corrugated board, 2.18 tonnes wood per tonne kraft paper bleached. Blue water requirements from ecoinvent database, with assumptions on water consumption (see Section 2.2.1)
Tea bag string	Cellulose fibre	Undefined	29	0	0	2.4	1	1	29	2.4	
Carton for primary packaging	Solid bleached board	Undefined	765	0	0	10	1	1	765	10	
Carton for secondary packaging	Corrugated board	Undefined	90	0	0	14	1	1	90	14	
Paper	Wood	Undefined	805	0	0	12	1	1	805	12	
Margarine tub and lid	Polypropylene	Undefined	0	0	0	3.0	0	0	0	3.0	Ecoinvent database, with assumptions on water consumption (see Section 2.2.1).
Margarine sealing	Aluminium and polyethylene	Undefined	0	0	0	42	0	0	0	42	Margarine sealing is made of 82% aluminium and 18% polyethylene by weight.
Concrete	Gravel and cement	Undefined	0	0	0	1.0	1	1	0	1.0	
Steel	Pig iron	Undefined	0	0	0	10	1	1	0	10	
Wrapping film	Polyethylene	Undefined	0	0	0	9.3	1	1	0	9.3	
Light fuel oil and diesel (per GJ)	Oil	Undefined	0	0	0	0.05	1	1	0	0.05	
Natural Gas (per GJ)	Gas	Undefined	0	0	0	0.01	1	1	0	0.01	
Electricity (per GJ)	Several	Germany	1.5	0	0	1.1	1	1	1.5	1.1	Electricity production profiles from IEA (2010). Water consumption from different power production technologies from Gleick (1994) and Gerbens-Leenes et al. (2008). Green water consumption related only to power produced from biomass
		UK	1.4	0	0	1.1	1	1	1.4	1.1	
		Belgium	1.5	0	0	1.1	1	1	1.5	1.1	
		Kenya	19	0	0	13	1	1	19	13	

[a] Locations for edible oils are only known at the country level. Regions within a country were estimated with Monfreda et al. (2008), USDA (2004).

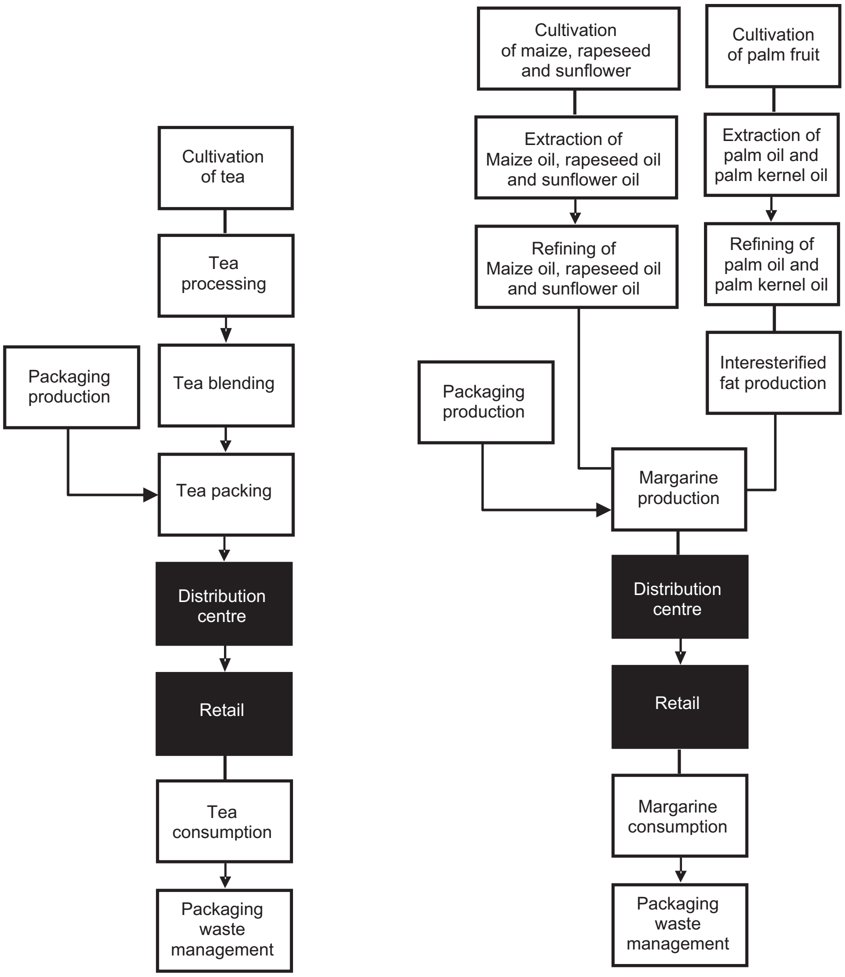

Fig. 1. Life cycles of tea (left) and margarine (right). Processes in black boxes are excluded in both water footprint and LCA. Packaging waste management is only included in LCA. Arrows indicate terrestrial or maritime transport steps.

In order to derive WF_{green} and WF_{blue} per tonne processed ingredient, product and value fractions were applied. The product fraction is used to reflect mass balances when processing raw materials, whereas the value fraction is used to allocate burdens between co-products based on economic value. Table 1 summarises the data used for all ingredients, including product and value fractions.

The blue water footprint associated with the production of packaging materials was estimated using the ecoinvent database (Hischier, 2007). It was estimated assuming that abstracted freshwater is consumed, with the exception of cooling water, where only 5% is assumed to be evaporated, as described above. Green water for paper and cardboard production was estimated based on the amount of green water consumed by tree growth (Gerbens-Leenes et al., 2008), and the amount of wood required in the paper and cardboard production processes, according to the ecoinvent datasets used (see Table 1).

The overhead supply-chain WF included several goods and services used in the factories that are not directly used in the production process. Following Ercin et al. (2010), only water footprints of concrete, steel, paper and energy (electricity and fuel) are selected in the overhead calculations. Water consumption for these inputs was also estimated from the ecoinvent database (Hischier, 2007; Kellenberger et al., 2007; Dones et al., 2007) with the same assumptions described above. Finally, green and blue water consumption in electricity production was estimated on a country basis (Table 1).

2.2.2. Operational WF

The operational water footprint is defined as the amount of freshwater consumed at a specific business unit, i.e. the direct freshwater consumption. In this study, the operational water footprints of the products included water incorporated into the product as an ingredient, water consumed during the production process, and an overhead WF related to e.g. drinking water and toilets. These components of the WF were calculated from data obtained from the tea and margarine factories.

2.2.3. Consumer WF

Margarine does not require water during use, as it is mainly used as spread. However, the indirect WF of keeping the product cool in the fridge was taken into account (Table 2). The electricity consumed was estimated as 0.074 kWh per tub of margarine (Milà i Canals et al., 2010a). For tea preparation the energy used to boil water was taken into account. According to Muñoz et al. (2008), the human body evaporates (through breathing and perspiration) 35% of the ingested water. This percentage was used to account for evaporated water in the tea study. The remaining 65% was assumed to be discharged to the same watershed where it had been previously abstracted, thus constituting a non-consumptive use.

Table 2
Summary of data used in the life cycle inventories of tea and margarine.

Process	Data and sources
Tea	
Agriculture (weighed average from Kenya, India, Indonesia)	Fertiliser dosage (1.8E-3 kg $NH_4H_2PO_4$, 0.029 kg NH_4HCO_3, 1.3E-3 kg KCl, 5.8E-3 kg K_2SO_4, 0.062 kg phosphate rock, 1.2E-3 kg $(NH_4)_2SO_4$, all figures per 50 g dry tea) obtained from suppliers, and from FAO (2009b) where supplier data were not available. The inventory included irrigation (3.9 L/50 g dry tea), calculated with the water footprint method, diesel fuel for machinery (4.1E-4 kg/50 g dry tea) and pesticide application (1.5E-7 kg active ingredient/50 g dry tea)
Processing	Fuel and electricity consumption for tea drying was obtained from suppliers, as 90 MJ kg^{-1} dry tea (95% of the fuel input as biomass, 1% light fuel and 4% electricity)
Transport to UK	Road distance from 300 to 1000 km. Maritime transport distances range from 11,000 to 16,000 km
Blending	Energy for blending in the Trafford Park factory is 2.54 MJ kg^{-1} dry tea (98% electric, 2% gas)
Packaging production	Packaging materials for a 50 g tea pack are the tea bag (kraft paper, 4.75 g), tag (kraft paper, 3.25 g), string (cellulose, 0.5 g), envelope (kraft paper, 14 g), box (solid bleached board, 13 g), overwrap, secondary, tertiary packaging (polyethylene film, 2.1 g), and secondary packaging (corrugated cardboard, 14 g)
Packing	Energy for packing in the Brussels factory is 4.9 MJ kg^{-1} dry tea (98% electric, 2% gas)
Use	125 L tap water are assumed to be used per kg tea (250 mL per cup) and 49.5 MJ electricity per kg tea (DEFRA, 2008) to boil the water with a kettle. 35% of ingested water is evaporated by the human body (Muñoz et al., 2008).
Waste management	Packaging recycling rates in Belgium were obtained from Duncan (2007). Recycling process is cut-off. Disposal of non-recycled packaging and tea leftovers consists of 13% landfilling and 87% incineration, which is the average disposal scenario for household waste in Belgium according to EUROSTAT (2010).
Margarine[a]	
Agriculture	Includes fertilizers, diesel fuel and pesticide use
Edible oil extraction	Includes steam, electricity and hexane consumption. Allocation between co-products is based on economic value.
Transport to refinery	Transport of palm oil and palm kernel oil involves a maritime distance of 14,800 km. The distance for sunflower oil is 11,500 km. Road transport of maize oil (150 km) and rapeseed oil 9650 km) is also included
Oil refining	Includes consumption of chemicals (activated carbon, bleaching earth) and energy (electricity, diesel fuel and steam). Allocation between refined oil and acid oil co-product is based on economic value.
Interesterification	Includes the energy use for the previous step of palm oil fractionation to obtain palm olein and estearine. Mass allocation was used in this co-production process. Enzymatic interesterification of palm kernel oil and palm estearine includes the consumption of bleaching earth and energy (natural gas and electricity)
Packaging production	Includes production of polypropylene tub and lid, aluminium-polyethylene sealing, as well as cardboard and shrinkwrap for secondary and tertiary packaging
Margarine production	Includes energy use in the plant (electricity, light fuel oil and natural gas)
Distribution	Not required, as the regional distribution centre and the factory are located in Pratau (Germany). Retail operations were excluded from the study.
Use	We estimated the energy requirements to keep the product refrigerated at home as 0.074 kWh per 500 g, based on the following assumptions (Milà i Canals et al., 2010): 21 days storage time, 75% of fridge volume actually usable, 0.0127 MJ L^{-1} day^{-1} and volume-to-weight ratio of the product of 1.5 L kg^{-1}
Waste management	Waste packaging is recycled, landfilled or incinerated according to the German scenario for each material. The recycling process is cut-off.

[a] For further details on margarine see Nilsson et al. (2010).

2.2.4. Impact assessment

The water footprint assessment starts with quantifying, localizing and describing the colour of the water footprint. Ideally the next step is identifying the vulnerability of the local water systems where the footprint is located, the actual competition over the water in these local systems and the negative socio-economic and environmental externalities associated with the use of the water. The impact assessment reported in this paper reflects an earlier stage of development in identifying impacts within water footprint studies. It focuses on identification of hotspots, following the approach of Ercin et al. (2010). We compare the blue water footprints of the ingredients with the water scarcity in the different regions where the water footprint is located. We defined the hotspots as the regions where the blue water footprint of products is large and where water scarcity is high. The level of water scarcity is taken from Smakhtin et al. (2004a, 2004b). We considered the water scarcity as high when the environmental water stress index (WSI) defined by Smakhtin is higher than 0.6. The environmental WSI is the ratio of the annual withdrawals in an area over the annual water availability in that area. The latter measured as the mean annual runoff (MAR) minus the environmental water requirements (EWR). Most recently an improved global water scarcity map has been published by Hoekstra and Mekonnen (2011). The environmental WSI thus represents the withdrawal-to-availability ratio with accounting for environmental water requirements. Assessment of the green WF sustainability is excluded from this study. The reason for this is that quantitative analysis of the sustainability of the green WF is a largely unexplored field. The difficulty lies in the estimation of green water availability. Particularly, data are lacking on the environmental green water requirement for preserving ecosystems and on the quantities of evapotranspiration that cannot be made productive in crop production.

2.3. LCA

2.3.1. Scope

The LCA studies aimed to quantify only impacts on water consumption, whereas other impact categories commonly assessed in LCA studies, such as global warming, acidification or eutrophication, are not discussed in this paper. The system boundaries included all the life cycle stages from cradle to grave. In summary this involves:

- Production and processing of raw materials
- Packaging production
- Transport of materials
- Product manufacturing
- Transport to regional distribution centre
- Use
- Waste management (packaging and product leftovers)
- Production of auxiliary materials and energy carriers

Transports to retailer and to the consumer household were neglected, as well as treatment of wastewater from tea consumption.

2.3.2. Data sources

For margarine a model from a previous LCA study on this product was used (Nilsson et al., 2010). For tea a model was built specifically for this study, using the same primary data sources used in the WF study. Table 2 shows a summary of the main assumptions and data used for both products in the inventory analysis. All background processes, such as energy carriers, transport services, fertilizers, pesticides and other chemicals were modelled with the ecoinvent database (Dones et al., 2007; Spielmann et al., 2007; Nemecek et al., 2007; Althaus et al., 2007). For electricity production, although ecoinvent datasets were used to model different production technologies, the country profiles were obtained from International Energy Agency statistics (IEA, 2010).

2.3.3. Water accounting

One of the key differences between LCA and the WF is that the former does not account for green water in the same way (Milà i Canals et al., 2009), while impacts on water quality (grey water) are dealt with by means of other impact categories such as eutrophication or freshwater ecotoxicity, which are not included in this work. Another difference is that the need to use consumed (rather than abstracted) water has only recently been recognised by the LCA community, and LCA inventory data is still predominantly abstracted water.

In the agricultural stage blue water consumption in irrigation was obtained from the corresponding WF calculations (Section 2.2.1). In the processing stage it was also possible to determine when water use is consumptive, since primary data sources were used. However in the background system (provision of fertilisers, energy carriers, packaging materials, etc.) this was not straightforward, as typically inventory data refer to abstracted water rather than consumed water. The assumption made was that all freshwater abstractions are consumptive, with the exception of water used for cooling, as already described in Section 2.2.1. Sea water abstraction as well as in-stream water use by hydropower plants described in inventory data were not considered as water consumption. Land use effects on the water balance (net green water) as described by Milà i Canals et al. (2009, 2010b) were neither considered.

2.3.4. Impact assessment

In Life Cycle Impact Assessment (LCIA) characterisation factors are applied to water volumes consumed in different regions, with the aim of generating an aggregated metric similar to what is done for carbon footprints. Different methods to obtain such characterisation factors have been proposed (Berger and Finkbeiner, 2010). The characterisation model used in the tea and margarine case studies is the WSI, as described by Milà i Canals et al. (2009, 2010b) for the impact category Freshwater Ecosystem Impact (FEI). FEI is measured as volume of ‘ecosystem-equivalent’ water. This concept is basically the same as the scarcity-weighed water volumes used by Ridoutt and Pfister (2010), referring to water volumes which are equivalent in terms of local scarcity. FEI is calculated as shown in Eq. (1):

$$\mathrm{FEI} = \sum_{i=1}^{n} \mathrm{CWU}_i \times \mathrm{WSI}_i \tag{1}$$

Where CWU_i is consumptive water use taking place in a river basin or region (L), WSI_i is the WSI value for the affected river basin or region, and i to n are the set of river basins, regions or countries in which water is consumed.

For their application in the LCA studies, WSI values were determined using the WaterGAP model (Alcamo et al., 2003). This model includes annual average WSI values on basin scale, taking into account environmental water requirements, as defined by Smakhtin et al. (2004a, 2004b). Site-specific WSI values were used for crop locations, whereas country averages were used for the remaining activities in the life cycle (Table 3). Conversion of basin WSI values to country WSI values was carried out using the Geographic Information System (GIS) ArcGIS v.9.2 (ESRI, 2010). Country level WSI values were calculated as the average from the river basins lying within the country boundaries, using river basin area as the weighting factor.

The application of WSI values in the characterisation step of LCIA requires knowing the regions where water consumption takes place. These are known for the foreground systems of both tea and margarine (crop cultivation, industrial processing, etc.), but not for their background systems (production of energy carriers, chemicals, etc.). Since the background data used in this study lacks the information detail to trace back the location of all individual water flows, the following assumptions were made:

- All background processes take place in the same country where the corresponding foreground process takes place. For example, water consumed in the life cycle of fertilisers used in Kenya is assumed to be consumed in Kenya.
- Most transport processes, either maritime or terrestrial, are international, thus it is not possible to directly assign a WSI to their water consumption. For this reason, and taking into account that water consumption associated to transports in these case studies constitutes a very small contribution, we decided to neglect them in the impact assessment phase.

3. Results of the case studies

3.1. Water accounting

Table 4 shows the results of the water accounting phase for the WF studies, measured in litres. The water footprints from various sources reflect the different proportions of the ingredients, while

Table 3
Water Stress Index values used in WF and LCA studies.

Country	Water Stress Index[a]
UK average	0.30
Belgium average	0.83
Germany average	0.55
Germany: Salzgitter	0.55
The Netherlands average	0.63
Kenya average	0.06
Kenya: Kericho	0.08
Kenya: Nyeri	0.07
India average	0.70
India: Cotagiri and Coonoor	5.20
Indonesia average	0.03
Indonesia: Agrabinta	0.01
Indonesia: Medan	0.20
Poland average	0.39
Czech Republic average	0.62
Czech Republic: Karlovy Vary	0.70
Hungary average	0.45
Hungary: Szederkeny	0.45
France average	0.33
France: Alsace	0.59
Argentina average	0.25
Argentina: Tres Arroyos	0.13
Ukraine average	0.49
Ukraine: Zaporizhia	0.48

[a] See Section 2.3.4.

Table 4
Water footprint results for the water accounting stage.

Process	Tea (L/50 g)			Margarine (L/500 g)		
	Green	Blue	Total	Green	Blue	Total
Supply Chain Water Footprint						
A) Ingredients	265	3.9	269	551	108	659
Black tea – Kericho plantation	46	0.002	46			
Black tea – Kericho smallholders	101	0.002	101			
Black tea – Nyeri smallholders	13	0.0004	13			
Black tea – Indonesia	85	0.001	85			
Black tea – India	20	3.9	24			
Rapeseed oil – Germany				91	0.2	91
Rapeseed oil – Poland				4.6	0.009	5
Rapeseed oil – Czech Republic				3.7	0.009	4
Maize oil – Hungary				5.3	6.9	12
Maize oil – France				4.3	2.3	7
Sunflower oil – Argentina				6.5	7.2	14
Sunflower oil – Ukraine				50	75	126
Interesterified fat of palm kernel oil and palm oil				385	16	402
B) Other components	29	0.6	30	1.7	0.4	2.1
Tea bag materials	18	0.3	18			
Packaging	11	0.3	11	1.7	0.4	2.1
C) Overhead water footprint[a]	0.9	0.7	1.5	0.2	0.2	0.4
Operational Water Footprint						
A) Water directly related to production	0	0.005	0.005	0	0.2	0.2
B) Overhead water footprint	0	0.003	0.003	0	0.03	0.03
Consumer Water Footprint						
A) Drinking water	0	2.2	2.2			
B) Electricity	0	2.8	2.8	0	0.3	0.3
Total Water Footprint	294	10	304	553	109	662

[a] Bulding materials, paper, and energy used in product factories.

Table 1 allows a direct comparison of materials in m^3/tonne. The WF of a carton of 25 tea bags is 294 L green water and 10 L blue water. In the case of margarine, the footprint is 553 L green water and 109 L blue water. In both margarine and tea the contribution of the operational and the overhead supply chain WFs is negligible as compared to the ingredients and packaging materials. The same was found by Ercin et al. (2010) in a pilot study on a soft drink.

The inventory results in the LCA studies are shown in Table 5 as 13 L for tea and 114 L for margarine. The water volumes are lower compared to the overall WF results, as in LCA only blue water is accounted for. In the case of tea almost 50% of the consumed water is related to the consumer stage, while in margarine the consumer stage is negligible and 73% of the consumed water is related to irrigation of sunflower.

The assumptions made, particularly that all freshwater abstractions are consumptive in the background system (except for water used for cooling) and concerning sourcing locations, mean that the estimates should be regarded as approximations. However, this does not affect the comparison of methods.

3.2. Impact assessment

For the impact assessment we first overlaid the map showing the geographical spreading of the water footprint of product ingredients and the global water scarcity map (Figs. 2 and 3). As seen from Fig. 2, the blue water footprint of tea production only occurs around Coonoor in India. Around 40% of the total blue water footprint of the tea product stems from this region. In addition, the region experiences high water scarcity (WSI>1). Therefore we only identified this region of Southern India as the hotspot for the tea product. On the other hand, it must be stressed that the percentage of tea from Southern India in the blend is relatively small (10%). It

Table 5
LCA results for the inventory and impact assessment stages.

Process	50 g tea		500 g margarine	
	Inventory (L)	Impact assessment (L ecosystem-eq.)	Inventory (L)	Impact assessment (L ecosystem-eq.)
Tea growing – Indonesia	0.6 (5%)	0.02 (0.06%)		
Tea growing – Kenya	0.2 (2%)	0.006 (0.02%)		
Tea growing – India	**4.1 (32%)**	**2.9 (76%)**		
Tea blending	0.1 (1%)	0.04 (0.2%)		
Rapeseed oil			2.0 (2%)	1.1 (2.2%)
Maize oil			9.4 (8%)	**4.8 (10%)**
Sunflower oil			**83 (73%)**	**37 (77%)**
Interesterified fat from palm oil and palm kernel oil			**18 (16%)**	0.03 (0.1%)
Margarine production			0.5 (0.4%)	0.25 (0.5%)
Packaging	1.0 (8%)	0.6 (2.3%)	0.5 (0.4%)	0.3 (0.7%)
Distribution	0.003 (0.02%)	0.001 (0.004%)	0	0
Consumer – electricity	**3.9 (30%)**	**3.3 (12%)**	0.4 (0.4%)	0.24 (0.5%)
Consumer – water	**2.2 (17%)**	**2.1 (7.9%)**		
Packaging waste	0.5 (4%)	0.4 (1.5%)	0.01 (0.01%)	0.007 (0.02%)
Total	13 (100%)	27 (100%)	114 (100%)	48 (100%)

Figures above 10% of the total value in bold.

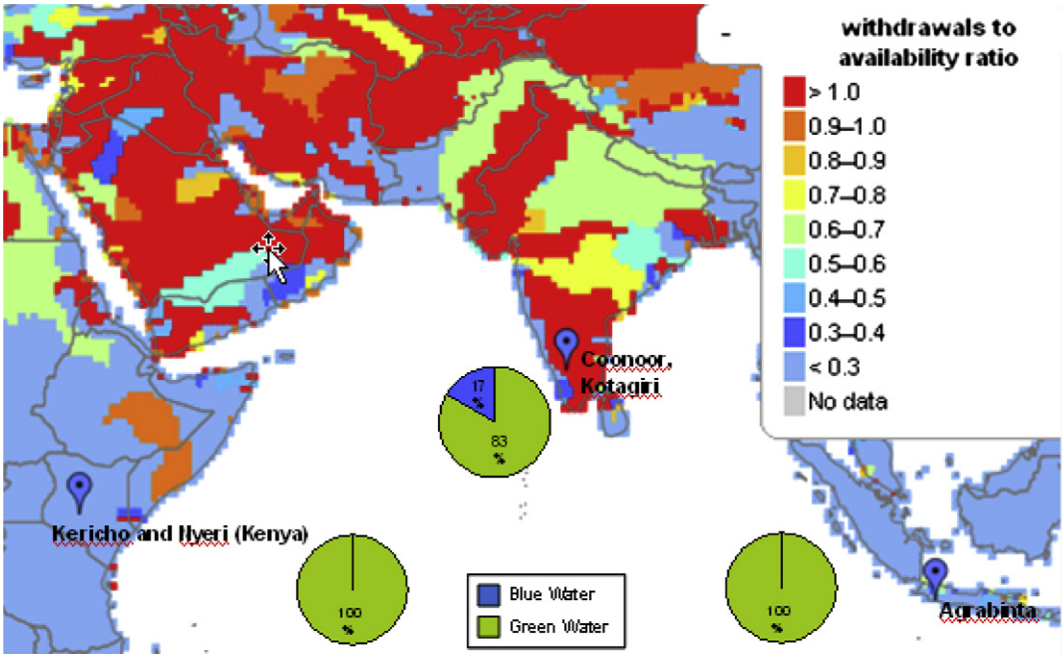

Fig. 2. Water footprint impact assessment, tea.

can be seen that growing tea in both Kenya and Indonesia are not hotspots as the WSI is lower than 0.6 in those regions and 100% of the WF is green in these locations, i.e. they are fully rain-fed.

Fig. 3 illustrates the overlay map for margarine ingredients. Margarine constitutes a rather more complex case study than tea, due to the higher number of crops and locations involved. The highest water scarcity is found in Karlovy Vary in the Czech Republic (WSI = 0.70). However, only 5% of the rapeseed oil is sourced from this location. In addition, the crop is entirely rain-fed, which means that the production from this region is not a hotspot. The sunflower cultivation in Ukraine can be considered as a potential hotspot although WSI is less than 0.6 (WSI is 0.48 in Zaporizhia) because most of the water used is blue water, and sunflower oil production in this country is responsible for 70% of the total blue water footprint of the product.

The results of the impact assessment phase in LCA are shown in Table 5. These results allow us to identify the most important processes or life cycle stages in terms of water consumption, taking into account the relative scarcity where water is consumed. It is worth noting that after applying the characterisation factors, the units of the inventory (L) and the impact assessment (ecosystem-eq. L) are no longer the same, and can only be compared on a relative basis, such as percentages. In the tea case study the WSI around Coonoor gives greater emphasis to this part of the life cycle than considering the volumes alone. For margarine, the impact assessment results highlight the relative importance of sunflower oil production, while the contribution from palm oil and palm kernel oil shrinks, as Medan in Indonesia has a low water-scarcity.

4. Discussion

4.1. Discussion of the results

Previous studies related to water consumption of similar products are scarce. In fact, we did not find any published study on water-related issues for margarine, whereas only two studies have been published on tea (Chapagain and Hoekstra, 2007; Mekonnen and Hoekstra, 2010). A WF of 17–34 L per cup of tea was estimated for the average Dutch consumption. Extrapolating these figures to 50 g tea leads to a WF of 283–567 L, which is in agreement with our estimate, lying in the lower part of this range. Nevertheless these studies have been applied with different system boundaries, since the present study includes packaging and also the consumer phase, whereas Chapagain and Hoekstra focused on water consumption in the agricultural stage. If packaging and consumer water are excluded in Table 4, the resulting WF of the studied tea is 269 L, below the range calculated by Chapagain and Hoekstra (2007). The differences are mainly due to origins of ingredients as WF values are very sensitive to the production locations of the agricultural inputs (different climatic conditions). Additionally the difference is due to higher yields considered in the present study, as wherever possible this information was obtained from suppliers rather than from FAO statistics, which provide average national yields.

The results of the impact assessment have identified tea growing around Coonoor and sunflower growing in Ukraine as potential hotspots for further investigation. These results must be taken with care, due to the level of uncertainty involved in the data used. In the case of sunflower, for example, we did not have data from suppliers, which meant we had to make some important assumptions: the theoretical irrigation requirements were assumed to be met, since the irrigation practices were not known. In addition, the yield was taken as the FAO country average, which tends to be low when compared to data from suppliers. Finally, it must be taken into account that sourcing varies from year to year, thus the sourcing proportions used in these case studies could be different in coming years.

Concerning application of the results in a business context, studies such as this may be used to identify potential risks (hotspots) which should be investigated further. Having identified with suppliers the crop–location combinations requiring attention, response strategies may then be developed to minimise impacts on water, within the broader context of overall sustainability.

The numbers are not precise, and are not appropriate for communication with customers and consumers; in some cases it is now possible to get more precise data (e.g. improvements in water database values for background processes) but other sources of

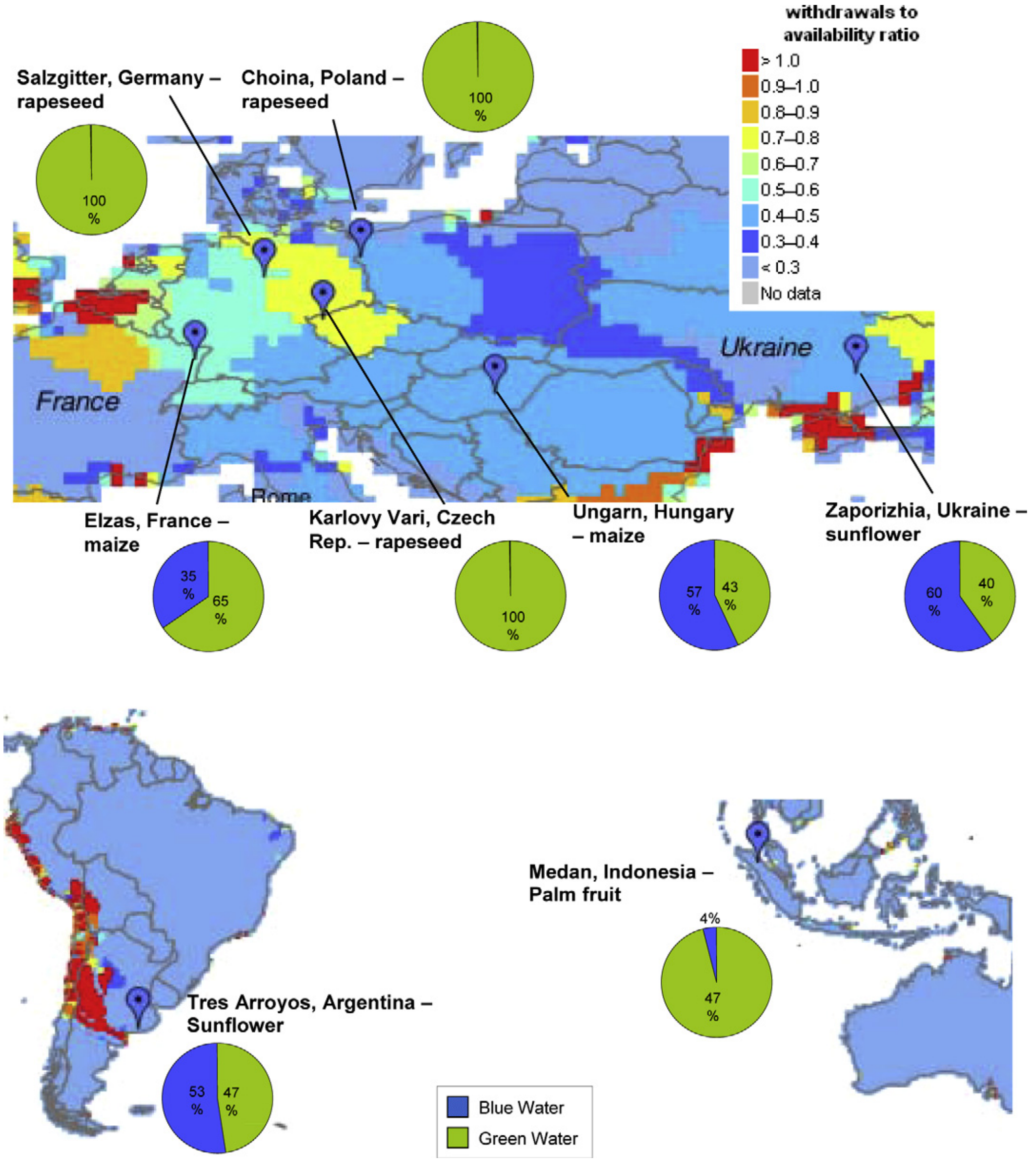

Fig. 3. Water footprint impact assessment, margarine.

uncertainty remain, for example precise sourcing locations. In this sense, it is important to strive for greater transparency in supply-chains.

The studies also showed that the operational and overhead water footprints were very small for these types of product, and provided evidence for simplification of the WF approach.

4.2. Comparison of approaches

LCA and WF come from different backgrounds and are useful for different purposes. LCA produces a single number for each impact category which seeks to describe the potential impact (e.g. on water scarcity) across the life cycle. With ingredients coming from regions of the world with very different scarcity, it is appropriate to weight the volumes in the different locations by characterisation factors which allow for this. Weighting has been shown to give quite different results over using the aggregated volume from the inventory (e.g. Ridoutt and Pfister, 2010), and some difference is seen here in both case studies. A single number is useful for communication purposes in summarising the potential impact of a product.

The WF approach has been developed from a water resource management perspective, and is strong in addressing the local and temporal nature of water-related impacts. The focus is not on the final number but on the components at the different locations. Quantifying and accounting for water use and related impacts in the appropriate time and spatial scales, could provide transparent information to improve water efficiency and develop robust corporate water strategies. Further analysis would investigate the particular water resources used, when the water is used, how else is water being used in the same area, and consider the sustainability of the water consumption at each location. A subsequent step would be to develop response strategies.

The methods have additional strengths and weaknesses. The methodology for calculation of blue and green water used by crops is well-established, and it also works well for individual factories. The strength of LCA is its robust systems analysis foundation, spanning several decades during which many issues related to defining the systems' function and boundaries have been debated and resolved. Water is considered alongside other impacts, and tools such as LCA software and data are well-established, particularly for water abstraction in industrial processes. Both the LCA and WF communities agree on the move to consider consumed water, which is complementary to abstracted water (UNEP-SETAC, 2010), an approach originally developed by the WF community. Table 6 seeks to summarise the strengths and weaknesses of the two approaches.

From a product level perspective, LCA and WF both seek to assess life cycle impacts on water resources. In fact, when using similar data sources, as is the case for the studies presented in this paper, they lead to similar results at the accounting/inventory stage, with the small differences due to slight differences in boundary conditions from applying the 'standard' methods. The fundamental difference is the inclusion of characterisation factors in LCA, rather than simply providing the volumes.

In spite of conceptual similarities, typically LCA and WF studies have a different scope and use different data sources. For example:

- WF includes green water, whereas LCA does not include it, or accounts for it differently.
- WF includes a grey water component to account for water pollution, whereas in LCA several impact categories are used to deal with water quality.
- LCA usually allows for an assessment of large systems, taking advantage of specific software and databases developed through the last two decades, mainly focused on water abstraction in industrial processes. WF is a more recent field and databases applying spatial and temporal detail are under development, particularly on the agricultural side.

The green water footprint measures the part of the evaporated rainwater that has been appropriated for the production of the products and is therefore not available for nature. Green water resources are limited and thus scarce, which gives an argument to account the green water footprint like blue water footprint. Besides, green water can be substituted by blue water and sometimes – particularly in agriculture – the other way around as well, so that a complete picture can be obtained only by accounting for both. In addition, having knowledge of a crop's total water consumption (blue and green footprints) allows managing potential future sourcing risks: a crop with a large green water footprint today may require a large blue footprint through irrigation tomorrow, if rainfall patterns change. However, green water consumption by the product system does not generally introduce significant changes in the local environment (i.e. as compared to green water evaporation if the system had not been established). Consequently green water is generally excluded from the impact assessment phase in LCA (Milà i Canals et al., 2009). On the other hand, the difference caused by the product system on rainwater availability to ecosystems may be included as the "land use effects on the water cycle" (Milà i Canals et al., 2009); Milà i Canals et al. (2010b) find a small contribution from these land use effects on the Freshwater Ecosystem Impact, and they have not been included in the present analysis. Further analyses are needed on this.

With regard to data availability, the WF offers a systematic approach to calculate water requirements by crops, which could be used by LCA practitioners, as shown in this paper. Beyond the farm boundaries, however, there is a general lack of data on water consumed by products and services. In this context, the WF community can take advantage of LCA databases and software tools, although as shown in our case studies LCA databases currently focus on water abstraction and lack the level of detail required to assess impacts on water resources. The growing interest in water by the LCA community is driving the improvement of existing inventory databases.

At the impact assessment level, WF and LCA address the same issues, but from different perspectives and with different purposes. In LCA single values are used to express impacts, whereas in WF single values are avoided (Hoekstra et al., 2009b). Despite this difference, we identified several common problems:

- The assessment requires knowing where all the processes involved in the life cycle take place, since water scarcity is local. This is in practice not possible with complex products, since

Table 6
A comparison of the LCA and water footprint approaches.

Aspect	LCA[a]	Water footprint[b]
Goal and scope	• Potential impacts of products and processes. Water use not traditionally assessed, except from the pollution point of view.	• Total consumed (blue and green) water in products and processes, plus (grey) water to assimilate pollution created by these processes. • Focus is to promote the transition towards sustainable, fair and efficient use of freshwater resources at the different scales (e.g. local, river basin, national, international)
Strengths	• Robust systems analysis foundation • Part of a holistic assessment across impact categories • Cradle-to-grave analysis • Tools facilitate ease of calculation for large/complex product systems. • Large databases available on all kinds of products and processes. • Methods (under development) allow for a regionalised impact assessment of water consumption, according to water scarcity and other variables. • Institutionalised: integral part of environmental management systems in industry, e.g. Integrated Product Policy in Europe)	• Strong for addressing the local and temporal nature of water-related impacts at localised level • Visual communication of footprint on maps, thus guiding the user to the location of hotspots • Well established approach for calculation of evaporated water, especially in agricultural processes.
Weaknesses	• Little data available on crop production • Green water is not included in available background data. • Available background data includes only abstracted (blue) water. Little information on consumption of water and spatial location. • Limited spatial and temporal resolution of impact assessment	• Current lack of extensive background data on consumed water in industrial processes. • Difficult to calculate and interpret impacts when large/complex systems are involved. • Current tools allow for cradle-to-gate analysis (although the methodology may be extended beyond this). • Regional water scarcity not incorporated into final footprint

[a] Carried out with LCA software and databases.
[b] Carried out with the method described in Ercin et al. (2010).

many supply chains are global and dynamic, and tracing back all processes is not feasible. Assumptions like those made in our case studies will therefore be required, or otherwise the system boundaries narrowed.

- For impact assessment, both approaches rely on the use of a water scarcity indicator. We used the scarcity indicator of Smakhtin et al. (2004a, 2004b), following the approach of Milà i Canals et al., 2009. Various improvements to this indicator have been suggested (Fingerman et al., 2011). The blue water scarcity index (Hoekstra et al., 2011; Hoekstra and Mekonnen, 2011) considers consumptive use, takes better account of environmental flows and is also available on a monthly basis. The variation factor and the logistic curve-fitting techniques introduced by Pfister et al. (2009) to account for climate variability and non-linearity of stress effects may also be considered. These were not available at the time of the study.
- We found that small basins tend to show disproportionately high WSI values as most water statistics do not consider water re-use: in a river the water is used several times before discharged to the sea, e.g. by factories located up- and downstream, and this is counted twice in the river's statistics, leading to higher WSI values.

5. Conclusions and outlook

Impacts on water resources across the life cycle of tea and margarine were assessed using the WF, following the Water Footprint Network guidelines (Hoekstra et al., 2009a, 2011), and LCA. The assessment included water accounting and impact assessment. The system boundaries were broader in the LCA studies, as LCA software and databases allow for inclusion of more background services. The WF (excluding grey water) of a carton of 25 tea bags (50 g of tea) is 294 L green water, 10 L blue water, and that of a 500 g tub of margarine is 553 L green water, 109 L blue water. The inventory results in the LCA studies, which correspond to blue water in the WF, are 13 L for tea and 114 L for margarine. The slight differences observed are due to differences in boundary conditions, although both methods have the potential for a full cradle-to-grave coverage of the products.

The philosophical differences between the methods are in the impact assessment; weighting the contributions due to scarcity in the LCA approach gives greater emphasis to tea-growing in Coonoor in terms of its potential impact on water scarcity. The WF approach comes from a watershed resource management perspective and focuses on the components at the different locations. Further analysis would consider the particular water resources used and investigate the sustainability of using the water. The LCA approach is useful for communication purposes and for presenting alongside other environmental impacts. The WFN approach provides transparent information on water use and related impacts in the appropriate time and spatial scales that could be useful to improve water efficiency and management.

From the experience of these case studies it seems that the LCA and the WF communities share the same challenges when it comes to the assessment of products. Therefore it is our opinion that potential synergies exist, since they rely on the same data for water accounting and impact assessment, and would benefit from further collaboration and joint development of methods.

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