Water Footprinting of Dairy Farming in Ireland

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Abstract

In the context of global water scarcity, water footprints have become an important sustainability indicator for food production systems. To improve the water footprint of the dairy sector, insight into freshwater consumption of individual farms is required. The objective of this study was to determine the primary contributors to freshwater consumption (i.e. water use that does not return to the same watershed) at farm-gate level, expressed as a water footprint, for the production of one kg of fat-and-protein corrected milk (FPCM), on 24 Irish dairy farms. This is the first study that uses detailed farm level data to assess the water footprint of a large set of Irish dairy farms. The water footprint comprises of the consumption of soil moisture due to evapotranspiration (green water), and the consumption of ground and surface water (blue water), and includes freshwater used for cultivation of crops for concentrate production, on-farm cultivation of grass or fodder and water required for animal husbandry and farm maintenance. The related impact of freshwater consumption on global water stress from producing milk in Ireland was also computed. Over the 24 farms evaluated, the production of milk consumed on average 690 L water/kg FPCM, ranging from 534 L/kg FPCM to 1,107 L/kg FPCM. Water required for pasture production contributed 85% to the water footprint, 10% for imported forage production (grass in the form of hay and silage), concentrates production 4% and on-farm water use ~1%. The average stress weighted water footprint was 0.4 L/kg FPCM across the farms, implying that each litre of milk produced potentially contributed to fresh water scarcity equivalent to the consumption of 0.4 L of freshwater by an average world citizen. The variation of volumetric water footprints amongst farms was mainly related to the level of feed grown on-farm and levels of forages and concentrates imported onto the farm. Using farm specific data from a subset of Irish dairy farms allowed this variability in WF to be captured, and contributes to the identification of improvement options. The biggest contribution to the water footprint of milk was from grass grown with green water, which is a plentiful resource in Ireland. This study also indicates an opportunity for present and future milk production systems to source feed ingredients from non-water stressed areas to further reduce the burden on freshwater resources, especially in countries that utilise confinement systems that have a higher proportion of concentrate feed in the dairy cow’s diet.

Key Words; grass, freshwater consumption, milk production, dairy sustainability, LCA

1. Introduction

Sustainable production of animal-source food has re-emerged at the top of the political agenda for two reasons, 1; demand for animal-source food will rise due to the increasing global population, rising incomes and urbanization (FAO, 2009; Steinfeld and De Haan, 2006; Wirsenius et al., 2010), 2; the challenge to produce animal-sourced food in a resource efficient manner (Aiking, 2014; Johnston et al., 2014; Steinfeld et al., 2013). There is increasing recognition of the tension between livestock production and water use (Busscher, 2012; Molden et al., 2011; Ridoutt et al., 2014), hence understanding the distribution and demands for freshwater in livestock production are of particular importance. Finite freshwater availability could become the main limiting factor for the global growth of the agri-food sector (UNEP, 2007). Quantifying the water footprint (WF) of agricultural outputs and identifying hot spots of water consumption along the food chain, therefore, is a first step in reducing the pressures on freshwater systems resulting from livestock production, while at the same time providing end user information.

Irish livestock production systems do not suffer water shortages or droughts due to Ireland's temperate maritime climate (Kottek et al., 2006). However, increasing the sustainability of milk production by reducing consumption of resources, such as water, will improve the marketability of Irish dairy exports (DAFM, 2010). The Irish dairy industry produces approximately 5.4 billion litres of liquid milk (0.7% of global production) and exports 85% of its annual production (DAFM, 2012). Moreover, Irish milk production is going through a period of rapid expansion due to the abolition of European Union (EU) milk quotas. This expansion is being supported by the Irish government who have identified the potential for an increase in output of up to 50% up to 2020 (DAFM, 2010).

To gain insight into the water use of Irish dairy farms, from cradle to farm-gate, the water footprint can be quantified, defined by the Water Footprint Network (WFN) as the sum of the volumetric water use along the entire supply chain of a product (Hoekstra and Mekonnen, 2011). This water footprint comprises of the consumption of soil moisture due to evapotranspiration (green water), the consumption of ground and surface water (blue water), and the degree of freshwater pollution due to wastewater discharges (grey water) (Hoekstra and Mekonnen, 2011). While green and blue water represent consumed water, grey water represents an emission. It has been argued, therefore, that grey water can be better represented in a life cycle assessment (LCA) (Jefferies, 2012; Milà i Canals et al., 2009; Pfister et al., 2009). Furthermore, volumetric water footprints alone highlight the intrinsic role of freshwater resources in production systems, but have been described as misleading (Ridoutt et al., 2009), as they fail to consider the environmental impacts of water use. The WF definition by the WFN, therefore, differs from the one used in LCA studies (Ran et al., 2016). Generally, LCA studies on WFs do not include green water, unless changes in the flow of green water are analysed. Furthermore, LCA studies tend to focus on assessing the environmental impacts associated with water use using metrics such a water scarcity and eutrophication potential (ISO, 2014). Efforts have been made in recent years by the LCA community (ISO, 2014) and IDF (IDF, 2010) to work towards a standardised WF method that would overcome the difficulty of WF interpretation and comparability due to differing methods. In this study, green and blue volumetric WFs were included, while grey water was excluded. Furthermore, an LCA mid-point indicator, i.e., the stress-weighted WF, was included to account for the environmental impact of blue water use (Pfister et al., 2009).

The environmental impact of freshwater use in dairying has been addressed in current literature (Palhares and Pezzopane, 2015; Ridoutt et al., 2010; Zonderland-Thomassen and Ledgard, 2012). Variation in results presented by those studies relate mainly to differences in assumptions regarding the composition and amount of feed consumed by animals, the sources and yields of animal feed crops and variability in outputs among production systems. To contribute to better insight into the demand for freshwater in a specific region and to improve the performance of individual farms, there is a need for water consumption studies to include detailed farm level data regarding climate, agricultural practices and utilisation of feed (Jeswani and Azapagic, 2011; Krauß et al., 2015; Ridoutt and Huang, 2012). The objective of this study was to determine the primary contributors to freshwater consumption up to the farm gate, expressed as a volumetric water footprint (WF) and associated impacts for the production of one kg of fat-and-protein corrected milk (FPCM), on 24 Irish dairy farms.

2. Materials and methods

2.1. System boundaries

Twenty four commercial dairy farms were selected from the Teagasc advisory database, referred to as study farms, which were located in the south and south-east of the country. Selection criteria included availability of herd and production data for 2013 and willingness of the farmer to collect and maintain data accurately. The system boundary was cradle-to-farm gate. Freshwater use quantified included water required for cultivation of crops for concentrate feed, on-farm cultivation of grass or fodder and water required for animal husbandry and farm maintenance, and was expressed per kg FPCM (CVB, 2000). Water use related to energy and fertilizer production was not included owing to its negligible contribution to the WF of milk production in the study by De Boer et al. (2013).

2.2. Data collection

Data on farm infrastructure were collected by means of a monthly survey. This included information relating to on-farm water sources (well/local government supply), types of milk cooling equipment and washing procedures of the milking machine and cow collection area. Water meters were also installed on each farm to record water volumes (m^3) throughout the farm including water used to facilitate milk production processes and water consumed by livestock. Domestic water consumption was measured separately and subtracted from the total water supply to determine water supply to the farm enterprise only. Water volumes were recorded on a monthly basis via an on-line survey with the farmers reading each of the installed meters and inputting the data into the online system. Additional information gathered included farm imports such as concentrate feed and forages. Milk production data were sourced from the Irish Cattle Breeding Federation (ICBF) records. Concentrate fed to dairy cows on the monthly farmer surveys (i.e. opening balance + purchased feed – closing balance) and feed ingredient composition and source information was taken from Upton et al. (2013) which was gathered from local feed mills. Raw data from water meter recording and surveys were exported to spreadsheets and subsequently used to compute the WF of individual farms. Economic allocation was used to allocate water consumption between dairy (91%) and beef production systems (9%) within a farm as this approach has been used for similar livestock systems (De Vries and de Boer, 2010; O'Brien et al., 2014; O'Brien et al., 2012), the more common biophysical approach to allocation (as recommended by the IDF (2010)) was not used but would have yielded similar results.

Table 1 describes the relative share of concentrate ingredients used in this study, country of origin and economic allocation factor for each crop. These data were sourced from Eco-invent (Ecoinvent, 2010) and Feedprint (Vellinga et al., 2013)

2.3. Water required for crop cultivation

Green and blue water consumption required during crop growth was calculated using the method described by (De Boer et al., 2013). Freshwater required to grow a crop can originate from precipitation and soil water (green water) or, in the case where water demand exceeds rainwater availability, from irrigation (blue water). All irrigation water was assumed to be consumptive, implying that irrigation losses did not return to the same water shed, representing a worst-case scenario (De Boer et al., 2013). Water which has been ‘consumed’ refers to loss of water when it is evaporated, incorporated into a product or returned to another catchment.

In order to assess the freshwater requirement for each input (concentrates, forages and grass), the volume of water required for all crops during the growing period was computed based on climate data from AQUASTAT (New et al., 2002), soil type and actual yield data (FAO, 2014; You et al., 2014). Grid data from the International Food Policy Research Institute (IFPRI) were used to identify the regions producing the majority of each feed ingredient, e.g. soybean originating from Argentina (Table 1). Actual crop yield data from IFPRI grid data were compared with the national average yield in 2012 (FAO 2014). Regionally specific yield data were scaled to the national average yield of that crop in 2012 by multiplying with the ratio of national average yield in 2012 over the national average yields from IFPRI. Soil type and characteristics within these regions were taken from a harmonised soil database (Fischer, 2008). AQUASTAT (Eliasson et al., 2003) was used to compute ET_o (mm/day), the evapotranspiration of the reference crop (Allen et al., 1998), for each specific crop location. The potential evapotranspiration (ET_p) over a crop’s growing period, assuming maximum soil water availability (Allen et al., 1998) was derived from AQUASTAT. The crop evapotranspiration requirement (ET_p, mm/period of growth) was calculated using the crop coefficient ($K_c[t]$) for the respective growth period and reference crop evaporation ($ET_o[t]$) summed over the period from sowing to harvest:

$$ET_p = \sum K_c[t] \; x \; ET_o[t] \qquad [1]$$

The crop coefficient K_c is crop specific and varies over time depending on the growth stages of the crop (initial, crop development, mid-season and late season). The sowing date, length of the growing period and K_c values of a desired crop were taken either from AQUASTAT or from the literature (Hoekstra and Chapagain, 2007).

Results from AQUASTAT were used to derive the rainfed evapotranspiration of the crop (ET_{rf}). Rainfed growing generally implies that the actual amount of soil water is less than the maximum potential amount of soil water. Therefore, ET_{rf} is ET_p corrected for lack of water during dryer conditions depending on soil moisture. ET_{rf} (mm/day) was calculated over the entire cropping period by:

$$ET_{rf} = \sum ET_p[t] \; x \; K_s[t] \qquad [2]$$

Ks[t], the transpiration reduction factor, necessary to consider water stress, was calculated daily as a function of maximum and actual available soil moisture in the rooting zone. Default values for effective root depth were defined in AQUASTAT. ET_{rf} is an estimate for the volume of evapotranspired precipitation (green water) of a crop over its growth period.

The actual crop yields were then used to calculate consumption of rainwater (green) and irrigation (blue) water in litres per kg of dry matter. The evapotranspiration from actual yield of a crop (Et_a, mm/ha) was derived from the relationship between water supply and crop yield described by (Doorenbos and Kassam, 1979):

$$ET_a = -((1 - Y_a/Y_p)/ky - 1) \; x \; ET_p \qquad [3]$$

Where Y_a is the actual crop yield per hectare, Y_p is the potential crop yield per hectare, k_y is the yield response factor, which is crop-specific and describes the relationship between evapotranspiration deficit and yield reduction, and ET_p is the potential ET requirement (mm/ha) of the crop. The potential crop yield Y_p was derived from the Agro-Ecological Zone method (Doorenbos and Kassam, 1979).

Irrigation was assumed to be absent where $ET_a \leq ET_{rf}$. When $ET_a \geq ET_{rf}$, irrigation volumes were calculated by:

$$Irrigation\,Volume = ET_a - ET_{rf} / Ir_{eff} \qquad [4]$$

Ir_{eff} is the irrigation efficiency, - a default efficiency of 0.7 was assumed for all crops (Allen et al., 1998).

2.3.1. Grass and silage utilisation

Annual grass and silage production and utilisation on each farm was modelled with the Teagasc Grass Calculator (Teagasc, 2011) using the difference between the net energy in units of feed for lactation (UFL) provided by external supplements (concentrates and forages) and the net energy demands of farm stock for maintenance, milk production and pregnancy as described by Jarrige (1989). This approach was utilised also by Mihailescu et al. (2014) to estimate grass utilisation over 21 Irish dairy farms. It was assumed that 1 UFL equates to 1 kg of dry matter of grass. The WF of the grass grown with a utilisation rate of 85% (O'Donovan and Kennedy, 2007) was then computed for each farm using equations 1 to 4 listed in the previous section.

2.4. Water stress index

The water stress index (WSI) is used to assess the related impact of freshwater consumption; it is considered a mid-point indicator assessing water deprivation and applies to blue water only (Pfister et al., 2009). A water stress index indicates the water consumption impacts in relation to water scarcity. The index stems from the water-to-availability (WTA) ratio. WTA is defined as the ratio of the total annual freshwater withdrawal for human uses in a specific region to the annually available renewable water supply in that region (Frischknecht et al., 2006). WSI values, ranging from 0.01 to 1 are derived using the following logistic function:

$$WSI = \frac{1}{1+e^{-6.4WTA*\left(\frac{1}{0.01}-1\right)}} \quad [5]$$

Where WTA* is a modified WTA to account for monthly and annual variability or precipitation and flows. The method can be applied at the country, region or watershed level. All total volumes of blue water in each region were multiplied by their specific regional WSI. to calculate a global average WSI. In order to calculate the stress-weighted WF per farm, each source of blue water use was multiplied by the relevant WSI (Table 2) and summed across the supply chain of the dairy system. To assess the global impact of freshwater use, the stress-weighted WF was normalised by dividing it by the global average WSI, giving a quantitative comparison of the pressure exerted from freshwater use through the consumption of a product (milk), relative to the impact of consuming 1 kg of water across the globe (Ridoutt and Pfister, 2010). The severity of water scarcity of water sheds is ranked as follows: WSI < 0.1 low; 0.1 ≤ WSI < 0.5 moderate; 0.5 ≤ WSI < 0.9 severe and WSI > 0.9 extreme (Pfister et al., 2009)

3. Results

3.1. General farm characteristics

Table 3 indicates the range of input and production details of the study farms in terms of size, production and national average comparisons. In 2013, the average study farm was 69 ha, produced 540,976 kg FPCM from a herd of 105 cows with an annual output of 5,238 kg FPCM per cow. Cows consumed 4,671 kg of dry matter (DM) feed per head per year, mainly from grass. Farm size, milk output, herd size and milk production per cow on the 24 study farms were greater than the national average farm. The study farms therefore, represent a larger than average dairy farm. With milk output and farm size expected to increase due to the abolition of milk quota, the results and conclusions drawn for these farms can be considered to be indicative of near-future milk production scenarios.

3.2. Analysis of green and blue water use

Table 4 presents the breakdown of water use into volumetric green water footprint (GWF), volumetric blue water footprint (BWF) and stress-weighted WF for on-farm water use (blue water only), concentrate water use, grass water use and imported forage water use. The sum of the volumetric GWF and volumetric BWF, as well as the total volumetric WF (i.e., both blue and green water) for each farm is also indicated.

3.2.1. Water footprint

The total volumetric WF of the 24 study farms ranged from 534 L/kg FPCM to 1,107 L/kg FPCM with an average WF of 690 L/kg FPCM (Standard Deviation (SD) 135 L/kg FPCM). The green water input into the dairy systems made up 99% of the WF with blue water making up the remaining 1%.

3.2.2. On-farm blue water footprint

On-farm blue WF refers to the volume of water used to facilitate the milk production processes and water consumed by livestock. In all cases this water was sourced from a well or public supply and, therefore, included blue water only. The on-farm volumetric BWF ranged from 1.2 to 9.7 L/kg FPCM with a mean value of 5.3 L/kg FPCM (SD 1.95 L/kg FPCM) and was 81% of the total BWF, while the remaining BWF was accounted for through concentrate production.

3.2.3. Concentrate water footprint

The average volumetric WF for concentrate production was 30.6 L/kg FPCM (SD 10.32 L/kg FPCM) with a range of 10.3 to 49.1 L/kg FPCM. Green water consumption in concentrate production made up 97% of the total water requirement for concentrate production. The contribution of concentrate production to the total volumetric WF equates to 5% in this study.

Table 1 shows the relative percentage share of ingredients in concentrates, the economic allocations and the share of green and blue water used during the growth of each crop. Blue water was used for irrigation of maize (Ukraine and USA), citrus meal (Brazil) and sugarcane molasses (Pakistan) and contributed <1% to the total WF per kg FPCM.

3.2.4. Grass water footprint

The grass water footprint refers to the water required for both grazed grass and on-farm produced silage. All grass growth was rainfed implying use of green water only. The mean grass WF was 579 L/kg FPCM (SD 129 L/kg FPCM) with a range of 413 L/kg FPCM to 1,045 L/kg FPCM. The grass water footprint made up on average 85% (range 51-96%) of the total volumetric WF per kg FPCM.

3.2.5. Forage water footprint

Cows were supplemented with imported forage when grass growth was insufficient to meet herd feed requirements. The use of forage varied over the farms in type and volume of forage utilised. Forages imported were predominantly in the form of grass silage, hay and maize silage. All imported forages were rainfed, utilising green water only. The average volumetric WF for brought in forage was 73.7 L/kg FPCM (SD 96.8 L/kg FPCM) with a minimum of 0 L/kg FPCM, where no forages are imported and a maximum of 366.3 L/kg FPCM. The water required for forage production made up 10% (range 0-45%) of the total WF per kg FPCM.

3.2.6. Stress-Weighted WF

The average stress-weighted water footprint for the production of milk from cradle to farm-gate for the 24 farms was 0.4 L/kg FPCM (range 0.1– 0.8 L/kg FPCM) with a S.D of 0.18 L/kg FPCM. The on-farm BWF made up 49% of this stress-weighted WF, irrigation water for growing of crops 50% imported forages, 1%.

4. Discussion

4.1. Volumetric water footprint international comparison

As 85% of Irish dairy products are exported, a comparison of the WF of Irish dairy systems to those in other regions is useful. Mekonnen and Hoekstra (2010) estimated that the production of 1 kg of Irish milk, on average, required 670 L of water, of which 633 L was green water and 37 L was blue water. In the current study, results showed a figure of 690 L of water per kg FPCM, of which 684 L was green water and 6 L was blue. In the current study the WF was higher for green water but significantly lower for blue water. The difference can be explained by differences in data collection. In this study, there were fewer estimations of the green water required for grazed grass and forage production and more precise data to determine on-farm blue water use compared to Mekonnen and Hoekstra (2010), increasing the accuracy of the WF. A Dutch study of milk production from a highly irrigated model farm, not representative of Dutch farming systems, reported that the production of one kg FPCM required 66.4 L of consumptive blue water (De Boer et al., 2013) of which 55% (36.8L/kg FPCM) was for irrigated on-farm grass growth, 18% (12.1 L/kg FPCM) was for irrigated on-farm maize production and 16% (10.3 L/kg FPCM) was for production of concentrates. Ridoutt *et al.* (2010) reported a volumetric blue WF of 14.1 L per L of milk produced in a temperate area of Australia on a pasture-based system supplemented by purchased hay and grain. Eighty three percent (11.7 L/kg) of this blue WF related to on-farm blue water use (i.e., drinking water and milking processes). Our results indicate that on average 82% of the blue WF (5.7 L/kg) occurred directly for day-to day milking processes and drinking water. A New Zealand study (Zonderland-Thomassen and Ledgard, 2012) compared the WF of dairy farming in two contrasting regions, Waikato (North Island, non-irrigated, moderate rainfall) and Canterbury (South Island, irrigated, low rainfall). The total volumetric WF was 945 L and 1084 L/kg FPCM for the two regions, respectively. The Waikato dairy system had a greater green WF, 72%, whereas in the Canterbury farm system green water constituted 46% of the WF. For both regions it was demonstrated that the green WF was associated with feed sources and grass growth. The blue water contribution in the Canterbury region was associated with irrigated pasture. It should be noted that the results in the studies discussed previously are influenced by methodological differences, which can affect direct comparability.

In the current study, there was a relatively large green water component due to the rainfed grass-based system of farming in Ireland which required fewer inputs by way of concentrates or other forages, thus there was a lesser demand for concentrates from irrigated crops. As well as this, only a small proportion of the components required for the production of concentrate required irrigation. Feed use was the largest contributor to the WF in Irish milk production. This finding is supported by other studies (De Boer et al., 2013; Palhares and Pezzopane, 2015; Sultana et al., 2014).

From a volumetric point of view 1 L of green water is equivalent of 1 L of blue water, but the impact of green water consumption on water scarcity according to the water stress index is negligible when compared to the impact of blue water consumption (Falkenmark and Rockström, 2006). Often the green WF of a good or service is considered of low importance, as green water has a low opportunity cost. Some of the literature does not include green water as green water is only available through the occupation of land and it is assumed that natural vegetation would consume a similar amount of water (Milà i Canals et al., 2009; Pfister et al., 2009). However, a growing number of authors highlight the importance of including green water as its inclusion demonstrates how rainfed agricultural systems reduce the demand and impact of blue water consumption (Aldaya et al., 2010; Chapagain, 2009; Mekonnen and Hoekstra, 2011). Including the green water consumption in this study demonstrates further the importance of green water in rainfed agriculture with 99% of the WF of milk production in Ireland being green water.

4.2. Impact of water consumption

The stress-weighted WF method used by Pfister et al. (2009) provides a characterisation factor for assessing the impacts of water consumption (i.e., blue water use) at river basin or watershed level. Based on this method, the stressed weighted impact of the production of 1 kg FPCM in this study was calculated to be 0.4 L H_2O-equivalents (H_2O-eq), implying that each litre of milk produced potentially contributes to fresh water scarcity, equivalent to the consumption of 0.4 L of freshwater by an average world citizen. This impact is due to the irrigation of crops for concentrate feed and on-farm blue water use. The production of molasses in Pakistan and maize gluten in the US were the main contributors to this impact as their associated water stress levels are high, accounting for 72% of the water stress related to concentrate production. The production of sugar cane and its subsequent processing to molasses in Pakistan had a WSI factor of 0.967. This WSI, related to 'extreme' water stress, was associated with the river Indus in the Punjab region where over 70% over Pakistan's sugar cane is cultivated. The maize gluten produced in the US was sourced from maize cultivated in an area with a WSI factor of 0.499, which is considered as 'moderate' water stress by Pfister et al. (2009). This indicates that the relatively small volumes of irrigation water used for the cultivation of concentrates in water stressed regions has a high impact compared to the on-farm blue use from a non-water stressed region such as Ireland.

Studies that consider the impact of blue water consumption related to milk production have reported values of 1.9 L H_2O-eq/L (Ridoutt et al., 2010) and 33.4 L H_2O-eq/kg FPCM (De Boer et al., 2013) on an Australian and Dutch model farm, respectively. The low impact of milk production in the Australian study was due to the farm being located in a region of Australia with plentiful water and a low WSI (0.013). The impact associated with the Dutch study was due to irrigated pasture and maize and the production of concentrates. In the study of Zonderland-Thomassen and Ledgard (2012) the impact of blue water consumption was

0.165 L H_2O-eq/kg FPCM for Waikato and 11.1 L H_2O-eq/kg FPCM for Canterbury. In the Waikato case, 92% of the associated impact was due to drinking water and water used in the milk harvesting process. Blue water abstracted for on and off-farm irrigation accounted for 94% of the impact in Canterbury, while 1% of the impact was attributed to animal drinking water. The WSI (0.017) of Canterbury was greater than in the Waikato region (0.0106), however these indices are both considered as low water stress regions.

4.2.1. **Monthly variation of the WSI**

During the year there are dry and wet seasons and consequently water availability changes. Seasonality may affect water deprivation due to evaporation requirements changing throughout the year. During warm seasons water deprivation is a larger problem compared to cold seasons. The production of different crops can result in a demand for irrigation water and can lead to greater water stress during a specific period of time. According to Pfister and Baumann (2012), monthly calculated WSI is crucial in areas with high variability of water use and availability. As a consequence, the original WSI calculations when used as guidelines for crop cultivation in different regions around the globe could provide an erroneous image about the actual potential water stress of a specific region or crop. The maize gluten for concentrate sourced from the USA has a growing period from May to early September. At time of sowing the water stress is low at 0.027, however as plant growth progresses into the initial stage, crop development and late season stages of development (July-September) the water stress increases substantially to 0.89. WSI data are accessible in Google Earth with the monthly determined WSI (Pfister and Bayer, 2014). As crop water requirements for sustained growth increase, so too does the localised water stress. The average annual WSI for the USA is 0.499 (Pfister et al., 2009) which does not account for the temporal changes in WSI over the growing period of a crop. If temporal changes in water stress are accounted for, then irrigation procedures undertaken at these times may result in an increased use of blue water, and hence an increased stressed weighted impact. According to Pfister and Baumann (2012), shifting crop growth locations may considerably reduce water stress. Further research on the use of blue water is needed to give better insight into temporal consumption patterns in countries which utilize irrigation in crop production.

Important considerations must be made in terms of the sustainability of future Irish milk production systems and milk production systems worldwide. O'Brien et al. (2012) show how high performing confinement systems in the UK and the U.S.A feed almost 10 times the volume of concentrates to dairy cows than Irish pasture based systems and, therefore, have a much higher demand on freshwater resources. While the results indicated here shed a positive light on the water resources required for Irish milk production, to fully consider sustainable production systems a future challenge will be for feed mills to source ingredients from areas of low water stress, in this case, sourcing maize gluten and molasses from regions with a low water stress grown predominantly from green water inputs. However, data on regional use of irrigation water in the producing countries of the world is not yet publicly available.

4.3. Exploration of volumetric water footprint variability

When the ranges of volumetric WFs over the 24 farms are compared, it is clear that although all farms utilise a grass-based milk production system the water consumption varies considerably. Farm number 17 had the lowest WF of all study farms with the lowest demand for on-farm blue water (1.2 L/kg FPCM) and no extra forages over the period of recording. This farm had a below average WF for concentrates (20.2 L/kg FPCM) and grass (512 L/kg FPCM), feeding 57 and 596 tonnes of concentrate and grass, respectively. The farm with the greatest WF (farm number 14; 1,107 L/kg FPCM) also had the greatest grass WF (1,045 L/kg FPCM) highlighting that the volumetric WF of milk production in Ireland is driven by the water requirements for grazed or ensiled grass due to the nature of rainfed grass based systems. Alternatively farm number 12 with a WF of 805 L/kg FPCM had a grass WF of 413

L/kg FPCM and a forage WF of 366 L/kg FPCM. This farm fed 378 tonnes of grass and fed 324 tonnes of imported forages. The WF of the imported forages contributed 44% to the total WF of farm number 12. Balancing the shortage of grass available with imported forages offsets the need to buy in extra concentrates, thereby avoiding increasing the farm's BWF. The large ratio of green to blue water indicated the sustainability of rainfed pasture based systems in the context of water consumption. This is a positive outcome for rainfed systems, but nevertheless, it is important to account for the proportion of inputs to a WF which are sourced from water stressed regions and work to reduce this burden, in this case the burden being water stress in Pakistan and the US for the production of molasses and maize gluten.

On-farm blue water use, while small in volume and having a low water stress is a source of water consumption that can be directly controlled by the farmer through management practices and choice of dairy farm infrastructure. The average volume of water consumed on the dairy farms was 2,964,053 L (range 982,000 - 6,325,326 L), equating to a WF of 5 L/ kg FPCM (range 1 to a WF of 10 L/ kg FPCM). While there is no shortage of blue water from the well supplies in Ireland on an annual basis, the availability of water can be limited during the summer months. During this time, the water requirements for drinking and milk harvesting is highest while local freshwater availability is lowest due to limited rainfall infiltration to recharge the well supply. The demand for on-farm freshwater can be lessened through water monitoring, together with improved milk harvesting technologies (i.e. water recycling) to reduce the on-farm blue water consumption at peak milking times (Murphy et al., 2014).

4.4. Green water availability and land use

Land use and changes in land use can have an effect on water availability and consumption (Milà i Canals et al., 2009). The green water consumed by growing grass has a low economic cost and could only be used for growing alternative crops or vegetation and could not be considered a substitute for domestic or industrial water requirements. In Ireland, grass growth is successful due to a number of different environmental factors. Ireland's temperate maritime climate and soil types mean that grass is used on 80% of the land suitable for agriculture. Grass, therefore, is the most important agricultural crop in Ireland and is essential in the output and viability of dairy farming in Ireland (Holden and Brereton, 2002; Shalloo et al., 2004).

To highlight the importance of rainfed grass systems the water required for the growth of grass across the farms in this study was evaluated against the total volume of available water from precipitation. The average volume of water required for the growth of grass was 286,082 m^3/farm (range 117,860 – 435,583 m^3). The average volume of water available through rainfall occurring on the farms was 751,514 m^3/farm (348,106 – 1,177,576 m^3). The water required for grass growth was on average 38% of the available rainfall occurring on the farms; however this is subject to seasonal variation. Furthermore, regions with poor growing potential, restrained by excess rainfall or heavy soils would be unsuitable for many other purposes such as arable production (O'Donovan et al., 2008). There is a consensus that by substituting ruminant systems with mono-gastric systems, and cropping systems, less land area would be required for food production (Hedenus et al., 2014; Wirsenius et al., 2010). However, the impacts do not consider the suitability of the occupied land for its use and the competition between land users. De Vries and De Boer (2010) highlight how the diets of pigs and poultry are rich in cereal products which could in a practical sense be consumed by humans directly. However, when arable systems are limited due to lack of suitable land, as could be considered in Ireland, ruminant systems on land unsuitable for crop production could be considered more sustainable (Peters et al., 2007; Van Zanten and Boer., 2015). When the water use efficiency is considered in this light it can be concluded that to feed grass, cultivated from green water, grown on land with few alternative uses (Ran et al., 2014), to ruminants with an ability to convert a non-human edible biomass such as grass into milk and meat is a productive use of available green water resources and thus more sustainable when considered from a water consumption point of view .

5. Conclusion

The application of a water footprint method addressing both volume and impact of freshwater consumption highlighted a significant variation in the WF of milk amongst grass-based dairy farms. This study presents the first WF assessment of Irish dairy farming using farm specific data, which does not currently exist in the literature. The results show the average WF of a subset of 24 dairy farms as well as the range of WF results over the farms demonstrating the variability in WFs that can exist from farm to farm; using farm specific data enabled this variation to be captured. The volumetric WF of milk produced by the 24 dairy farms was on average 690 L/kg FPCM; consisting of 684 L/kg FPCM green water and 6 L/kg FPCM blue water. Only 1% of the water footprint was blue water used for farm processes (drinking and milking) and for irrigation. The average stress weighted water footprint was 0.4 L/kg FPCM across the farms, implying that each litre of milk produced potentially contributes to fresh water scarcity, equivalent to the consumption of 0.4 L of freshwater by an average world citizen. Furthermore, the study indicates that the biggest contribution to the volumetric WF of milk is from grass grown with green water, a plentiful resource in Ireland. Our results show that green water inputs dominate over blue water inputs, irrespective of farm. The utilisation of green water available at a low opportunity cost to produce milk demonstrates the sustainability of milk production in Ireland with respect to water consumption. This study also indicates an opportunity for present and future milk production systems to source feed ingredients from non-water stressed areas to further reduce the burden on freshwater resources, especially in countries that utilise confinement systems which have a higher proportion of concentrate feed in the dairy cow's diet. This poses a potential challenge for the sustainability of these systems from a water footprint point of view.

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TABLES;

Table 1. Relative share of various ingredients by dry matter input (including country of origin), economic allocation and the percentage share of green and blue water requirements for each crop.

Crop[1]	Origin	Economic Allocation[2] %	Ingredient Share %	Green %	Blue %
Wheat	Ireland	93	3%	100	
Barley	Ireland	90	3%	100	
Maize Grain	Ukraine	10	5%	96	4
Soybean hulls	Argentina	59	16%	100	
Palm Kernel	Malaysia	1	4%	100	
Rapeseed	Canada	25	15%	100	
Citrus Pulp	Brazil		17%	82	18
Maize Gluten Feed	USA	8	8%	74	26
Molasses (Sugarcane)	Pakistan	5	6%	50	50
Distillers Grains	Ireland	30	17%	100	
Vegetable oil		17	3%	100	

[1] Feed ingredient and origin information (Upton et al., 2013)

[2] Source: (Ecoinvent, 2010; Vellinga and Blonk, 2012; Vellinga et al., 2013)

Table 2. Value for water stress index (WSI, dimensionless, ranging from 0-1) and the level of water stress for the relevant country.

Country	**WSI[1]**	**Water Stress Level**
Argentina	0.352	Moderate
Brazil	0.066	Low
Canada	0.102	Moderate
Ireland	0.022	Low
Malaysia	0.043	Low
Pakistan	0.967	High
Ukraine	0.3	Low
USA	0.499	Moderate
Global average	0.602	Moderate

[1] (Pfister et al., 2009)

Table 3. Production parameters for study farms compared to national average (CSO, 2013; DAFM, 2012).

Farm #	Farm Area (Ha)[1]	Milk Sales (kg FPCM / year)[2]	# Cows	Milk Production / Cow (kg FPCM /year)	Concentrate (T DM/year)[3]	Grass Grown (T DM/year)	Imported Forages (T DM)	Kg Feed / Cow per year	On-Farm Water Requirements (Litre/year)[4]
1	57	413,841	78	5,306	47	522	12	6693	2,863,154
2	82	523,937	115	4,556	64	557	6	4841	3,594,873
3	32	297,591	45	6,613	49	221	0	4907	2,092,755
4	105	522,517	126	4,154	93	449	88	3569	1,988,154
5	40	385,463	73	5,266	49	321	56	4380	2,310,749
6	47	441,206	74	5,962	67	324	58	4376	5,057,710
7	90	903,501	149	6,064	116	709	17	4759	3,293,440
8	81	815,619	143	5,720	34	623	258	4370	3,716,382
9	88	767,558	148	5,172	76	693	14	4673	3,971,921
10	73	533,843	108	4,943	69	473	28	4378	2,439,719
11	85	855,551	194	4,406	57	671	45	3457	4,137,530
12	61	615,095	117	5,257	59	378	324	3233	3,404,673
13	48	298,268	49	6,087	37	262	0	5341	2,676,703
14	75	303,635	71	4,277	58	500	3	7045	2,060,491
15	108	719,870	161	4,482	95	704	11	4382	6,325,326
16	81	679,721	123	5,517	87	571	23	4635	2,553,000
17	76	730,660	117	6,245	57	596	0	5093	982,000
18	72	456,317	88	5,162	46	419	3	4740	1,944,600
19	58	511,692	97	5,254	66	464	0	4760	4,701,600
20	50	378,130	70	5,402	28	333	4	4758	1,869,400
21	39	307,405	72	4,246	47	306	8	4222	1,999,351
22	53	344,280	70	4,918	58	288	0	4120	1,826,261
23	82	597,535	111	5,403	49	467	50	4225	3,300,200
24	75	580,190	110	5,294	26	565	8	5159	2,027,270
Min	32	297,591	45	4,154	26	221	0	3,233	982,000

Avg	69	540,976	105	5,238	60	476	42	4,671	2,964,053
Max	108	903,501	194	6,613	116	709	324	7,045	6,325,326
Nat Avg.[5]	57	316,000	66	4,788	66	627	NA[6]	4936	NA

[1] Ha = Hectares

[2] FPCM = fat and protein corrected milk

[3] T DM = Tonnes dry matter

[4] On-farm water requirements = total volumes of water used by each farm for day to day milk production processes over the monitoring period (all blue water).

[5] Nat Avg. = National Average

[6] NA = Not Available

Table 4. Calculated blue water footprint (BWF), green water footprint (GWF) and stress weighted WF of study farms in litres of water / kg FPCM of milk sold from cradle to farm gate.

Farm#	On-Farm[3] BWF	Feed GWF	Feed BWF	Grass GWF	Forage GWF	Forage BWF	Total GWF	Total BWF	Total Volumetric WF	Stress Weighted[4] On-Farm BWF	Stress Weighted Feed BWF	Total Stress Weighted WF
1	6.4	30	1.1	787	157	0	974	7.4	981	0.3	0.5	0.8
2	6.5	33	1.2	706	11	0	750	7.7	758	0.3	0.3	0.5
3	6.7	45	1.6	496	0	0	541	8.3	549	0.3	0.3	0.5
4	3.4	45	1.6	579	197	0	821	5.0	826	0.1	0.1	0.3
5	5.2	32	1.1	496	246	0	774	6.3	780	0.2	0.2	0.4
6	9.7	37	1.3	438	178	0	653	11.1	664	0.4	0.4	0.8
7	3.4	35	1.2	512	21	0	568	4.7	572	0.1	0.1	0.3
8	3.9	10	0.4	453	181	0	644	4.3	649	0.2	0.2	0.3
9	4.7	25	0.9	562	43	0	630	5.6	636	0.2	0.2	0.4
10	4.5	36	1.3	611	65	0	712	5.7	718	0.2	0.2	0.3
11	4.7	18	0.6	520	63	0	601	5.3	606	0.2	0.2	0.4
12	5.2	26	0.9	413	366	0.9	805	7.0	812	0.2	0.2	0.4
13	8.0	32	1.1	570	0	0	601	9.1	611	0.3	0.3	0.7
14	6.1	49	1.8	1045	5	0	1099	7.9	1107	0.2	0.2	0.5
15	8.0	34	1.2	629	8	0	672	9.2	681	0.3	0.3	0.6
16	3.4	33	1.2	535	77	0	645	4.6	649	0.1	0.1	0.3
17	1.2	20	0.7	512	0	0	532	1.9	534	0	0	0.1
18	3.9	26	0.9	601	15	0	642	4.8	647	0.2	0.2	0.3
19	8.4	33	1.2	568	0	0	602	9.6	611	0.3	0.3	0.7
20	4.5	20	0.7	565	24	0	609	5.2	614	0.2	0.2	0.4
21	5.9	40	1.4	625	62	0	727	7.3	734	0.2	0.2	0.5
22	4.8	44	1.6	555	0	0	599	6.4	605	0.2	0.2	0.4
23	5.0	21	0.8	513	41	0	576	5.8	582	0.2	0.2	0.4

24	3.2	12	0.4	615	9	0	635	3.6	639	0.1	0.1	0.3
Min	1.22	10	0.4	413	0	0	532	1.9	534	0	0	0.1
Avg.[1]	5.28	31	1.1	579	73.7	0	684	6.4	690	0.2	0.2	0.4
Max	9.74	49	1.8	1045	366.3	0.9	1099	11.1	1107	0.4	0.5	0.8

[1] Avg. = Average

[2] On-farm WF = Refers to water used by each farm for day to day milk production processes over the monitoring period (all blue water).

[3] Stress Weighted = Stress weighted WF, weighted using the water stress index.

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