The Water Footprint of English Beef and Lamb Production

– A report for EBLEX

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Abstract

Recent reports highlighting large quantities of water required to produce a kilo of meat have attracted media attention, leading to debates over the role of meat in a sustainable diet. Such reports frequently quote figures based on global averages and therefore conceal significant regional variation, ignoring the source of the water required and local climatic conditions. This report attempts to quantify the water footprint of English beef and lamb production, combining the water simulation model Wasim and the Cranfield Life Cycle Assessment model to calculate the water required to produce a tonne of beef and lamb meat. This method accounts for all water required by grass and crops in addition to drinking water and other requirements. Water use is considered in three categories; green, blue and grey water. Results show that beef has a water footprint of 17,700 m^3/t carcase weight and lamb 57,800 m^3/t. Of these, 84% and 97% respectively is green water use, i.e. evapotranspiration of rainfall on crop and grassland. Without this breakdown there is no distinction between rainfall and irrigation supply (blue water), which means that UK beef production may appear similar in impact to countries where irrigation of feed crops is dominant. This report highlights the importance of considering water use in context; in this case, for a temperate, wet climate such as England where crop and grassland water requirements are adequately met by green water from rainfall. Upland and hill production systems have higher water footprints, mostly because grass yield is lower. However, it is shown that rainfall surplus per tonne grass production is still highest in these regions, so that export of water for other human purposes is possible from these regions.

Introduction

Recent stories in the mass media have discussed the amount of water required to produce meat. Large figures have been quoted for the amount of water required to produce a kilogram of meat, leading to debates over the role of meat in a sustainable diet and even suggestions that consumers may “face the prospect of rationing” (Daily Telegraph, 2009). The figures quoted are usually averages of 15,500 L/kg for beef and 6,000 L/kg for lamb. However, these global averages conceal significant regional variation. For example, Hoekstra & Chapagain (2007) quote figures for beef ranging from 11,000 L/kg in Japan to 37,800 L/kg in Mexico.

More importantly, few of these studies consider the source of the water used and therefore the impact of this water use on the environment or other water users. If livestock are fed on concentrates produced under irrigation in water stressed environments, this water use may have a significant impact, however, if they are fed on grass grown under rainfed conditions, the impact of water use may be negligible. In this respect, UK livestock production is very different to drier regions, such as parts of North America, where much of the diets are sourced from crops grown in dry areas and irrigation is more common than in the wetter UK. In the UK, a large proportion of feed consumption for many production systems is grazed grass or silage. For beef cattle fed on more cereal-based diets, only 0.4% of cereal crops are irrigated (Weatherhead, 2005 and Defra, 2010a).

The concern about water also begs the question; what is the meaning of “required” or “used” in this context? Once fossil fuel is used, it changes its chemical form and releases water and CO_2 as main end products. In contrast, water does not change its chemical form. It may change state (e.g.

evaporate), move locations (e.g. within organisms or through rivers), become polluted or dilute other polluted waters.

The water footprint concept

The water footprint concept was developed by Hoekstra and Hung (2002) as a measure of a nation's appropriation of global water resources. It can be considered to be the sum of the all the water used in the production of the goods and services consumed by a nation (or an individual or organisation). Such figures are useful to convey the magnitude of an activity's dependence on freshwater systems, however, in order to make the water footprint estimate more useful, it is common to differentiate between blue, green and "grey" water footprints.

Green water is the rainfall that is used by a crop at the place where it falls (Falkenmark, 1995). Most UK crop production is rainfed, therefore most of the water footprint of UK cropping comprises green water with a low opportunity cost - if that water were not being used to grow rainfed crops, it would not be available for other uses. Assuming the field is not kept bare, some other vegetation (e.g. unmanaged vegetation) would potentially use a similar amount of water. There is, therefore, little benefit to be gained by reducing the green water component of the water footprint.

Blue water is water that is abstracted from water resources such as rivers, lakes and groundwater. Water used for irrigation, feed processing, animal drinking and washing is blue water and has competing uses. It has a higher opportunity cost to society than green water in that, if that water were not being abstracted for livestock production, it would be available for others to abstract (e.g. domestic water supply or industry) or for environmental uses (e.g. maintenance of river flows and wetlands, protected habitats). Even in a relatively wet climate, such as in England, rising demand for water and increasing competition between sectors is highlighting the threats to blue water for agriculture. Much of south and east England is considered to subject to serious water stress (Environment Agency, 2007).

Grey water is defined as "the volume of freshwater pollution required to assimilate the load of pollutants based on existing ambient water quality standards" (Hoekstra et al., 2009). It is calculated as the volume of water required to dilute pollutants to an acceptable level such that the quality of the ambient water remains above defined water quality standards. In the case of beef and sheep production, this calculation could be based on many variables and unknowns and therefore has been excluded from the main water footprinting exercise, though a quantitative example is provided later.

This study reports the quantification of the total freshwater used in the production of beef and lamb in England.

Approach

The total water footprint of lamb or beef comprises the following elements, which are additive:

Source	Green water	Blue water	Grey water
Drinking water		✓	
Washing and cleaning		✓	✓
Feed processing		✓	✓
Embedded water in diet	✓	✓	✓

The components are described below together with their summations.

Drinking water

Calculations for drinking water requirements for beef and sheep production were based on data from a recent study for Defra (Thomson et al., 2007).

For beef production, water requirement was based on dry matter (DM) intake, dependent on ambient temperature, Table 1. The water intake comprises both water in feed and drinking water.

Table 1 Drinking water requirements of cattle, ARC review, cited in Thomson et al. (2007).

Drinking water per kg DM intake	Water intake, L/[kg DM]
At <10C	3.5
At 11-15C	5.4
At 16-20C	6.1
At 21-25C	7

This was incorporated into the Cranfield Life Cycle Assessment model (Williams et al., 2006), using temperature data for three representative sites across England from the South West, West Midlands and North West. An average ambient temperature was estimated based on the number of months and time of year expected for each growing period/production system. For dairy beef, all production was assumed to be in lowland areas and thus an average temperature of 10°C was taken. As an example, for suckler beef, spring-born intensive cereal beef calves are assumed to be finished between October and May for which the average ambient temperature for the lowland representative site was calculated as 7.3°C and thus water intake is assumed to be 3.5 L/kg DM. Water in feed was extracted from feed consumption data and a drinking water requirement was taken as the balance of total water requirement and water in feed. For lactating suckler cows, it was assumed that 55% of water intake came from feed and thus the remaining balance was considered to be blue drinking water.

Standard drinking water values for ewes and lambs were also taken from Thomson et al. (2007), Table 2.

Table 2 Drinking water requirements of sheep

	Drinking water, L animal^{-1} day^{-1}
Ewes	4.50
Rams & other adult sheep	3.30
Lambs	1.68

Washing and cleaning water

For both sheep and adult and young cattle, there is apparently no wash water requirement during or following the housing period, although some may be used for cleaning trailers. No data were available for this activity, but it is likely to be very small compared with drinking. Water for dipping sheep does contribute to the blue water consumption of sheep production, Thomson et al (2007). Their value of 2.25 L head^{-1} for sheep dipping was used in the model.

There is no formal uncertainty analysis associated with drinking water and dipping water consumption for beef and sheep, however it is likely that with natural variation a coefficient of variation (CoV, defined in the Glossary) of 5-10% could be assumed.

Embedded water in the diet

The feed given to animals contains 'virtual' or 'embedded' water. This includes all the physical water in the harvested crop and the water used by the growing plant and transpired from the leaves, i.e. green water. It also includes blue water used in commercial feed processing. Evapotranspiration accounts for more than 99% of the total water use of most crops. A significant part of the water footprint of meat production is expected to be the virtual water used in the production of feed.

Livestock in England are fed on a wide range of feeds depending on location, price and availability. Apart from grass, the main feeds are derived from domestically produced wheat, barley, oilseed rape and sugar beet and imported soya. For each, the water footprint is determined from the total crop water use (ETc) over the growing period of the crop and the crop yield, thus

$$WF = 10\frac{ETc}{Y}$$

where:

WF = Water footprint, m^3/t

ETc = crop water use, mm

Y = crop yield, t/ha

and 10 is a scalar to ensure consistent units.

Domestically grown concentrated feed crop production

The water footprints of domestic cereals and oilseed crops were estimated as if produced in the eastern counties of England. For sugar beet, the East Midlands region was also considered.

Daily weather data (rainfall and reference evapotranspiration, ETo) were collated for four stations in eastern England for as many years as possible in the baseline reporting period 1961-90. The evapotranspiration data was only applied to each crop's growing season (in accordance with Hoekstra et al, 2009). Cropping dates and crop parameters for winter wheat (W), spring barley (B), winter oilseed rape (OSR) and sugar beet (SB) were estimated from Holman et al., (2005) for agroclimatic zone 6. Crop water use was estimated from a daily soil water balance using the Wasim model (Hess and Counsell, 2000). Average yields for Eastern England for 2008/09 were derived from the Farm Business Survey (Defra, 2010b). Two stations in eastern England (that account for 56% of the national sugar beet area) and one in the East Midlands (that accounts for 20%) were taken as representative of the sugar beet area.

The estimated water footprints, per tonne of feed, are shown in Table 3.

Table 3 Estimated water footprint of home grown feed crops

Feed source	ETc mm	Yield t FW/ha	Green WF m^3/t FW	Blue WF m^3/t FW	Total WF m^3/t FW
Winter Wheat (UK)	537	8.97	599		**599**
Spring Barley (UK)	490	6.66	736		**736**
Oilseed rape (UK)	494	3.09	1,599		**1,599**
Sugar Beet (UK)	516	63.5	80	1	**81**

Winter wheat, spring barley and winter oilseed rape are all rain-fed in England so the entire water footprint of these crops is green water. Other crops such as winter barley, feed bean and maize silage were estimated from the above results. A crop like winter barley evaporates a similar amount of water to winter wheat, but has a yield similar to spring barley, so winter barley is justly represented by the mean water footprint of the these two crops. Most sugar beet grown in England is rainfed. Only 8,487 ha of sugar beet were irrigated in England in 2005 (Weatherhead, 2006) out of a total area of sugar beet of 148,300 ha of crop grown (Defra, 2010c). This is only 6% of the total crop, however, the blue water footprint was also estimated for completeness.

Feed processing

An average water use of 45 L/t feed was used, based on data from within the feed industry. This is all blue water and is mainly used for steam raising and replacing evaporated water from heat-processed feeds to ensure a constant DM concentration in feeds. It was assumed that 75% of concentrated feeds were processed commercially and thus used blue water, with the rest being home processed without water.

Imported soya

The water footprint of imported soya was estimated for two locations; Cordoba region of Argentina and Goias region of Brazil. It was assumed that equal amounts were used from the two countries, which is a slight simplification of data from Defra's import statistics. Long-term average climate data for representative stations were extracted from the FAO CLIMWAT database (FAO, 2010a) and cropping dates estimated from the FAO GIEWS country briefing papers (FAO, 2010b). Average yields (2007-2008) were estimated from the FAOSTAT database (FAOSTAT, 2010). Crop water use per tonne of feed was estimated using the CROPWAT Schedule method with the irrigation option set to "no irrigation", Table 4.

Table 4 Estimated water footprint of Brazilian and Argentinean soya beans

Feed source	ETc mm	Yield t FW/ha	Green WF m^3/t FW	Blue WF m^3/t FW	Total WF m^3/t FW
Soya (Argentina)	595	2.90	2,052		**2,052**
Soya (Brazil)	454	2.82	1,610		**1,610**

The figures for imported soya are 50% and 80% higher than the figures quoted by Hoekstra and Chapagain (2008) for soya in Argentina and Brazil respectively. Allowing for the method they used, their figures would suggest yields around 4 t/ha, which is higher than those given by FAOSTAT. It was assumed that all soya production was rain-fed, as average seasonal crop evapotranspiration, (Etc), was greater than, or close to average seasonal rainfall in both production locations**.**

The inclusion rates of soya meal in beef and sheep concentrate feeds was 5.5%, with the amount of concentrate feed consumed dependent on the production system. A sensitivity analysis for this inclusion rate is given in Appendix 2: Sensitivities.

Grazing, hay and silage

The yield and quality of grass grown for grazing and silage production cover wide ranges, owing to variations in land quality and rainfall. Grass DM production was estimated using site classes. Site class definitions are based on the water-holding capacity of the soil, summer rainfall and altitude, mainly because temperature falls with increasing altitude (Soffe, 1995). Low summer rainfall restricts growth and high water holding capacity enhances growth. The most productive grassland has a site class of 1 and 7 is the least productive. Areas with a high site class number have a lower yield potential and are thus found in less favourable upland/hill areas such as the Lake District and North York Moors.

The Cranfield LCA model calculates potential grass and silage yields for each site class from soil texture, rainfall and altitude and thus these yield values were extracted and used for this study, Table 5. The average water use of grass (ETc) was calculated using the method of Hess (2010). This was applied using rainfall and reference evapotranspiration (ETo) data for each 5 km grid square in England and Wales. The weighted average site class for each grid square was also calculated (Figure 1) and matched with the expected grass yield for that site class. The green water footprint was thus calculated as the average for each site class from the 5 km grids (Table 5). Grass yield decreases with increase in site class, often with altitude particularly for site class 7, and thus the green water footprint of grass and silage, per tonne or per hectare, increases markedly for very high site classes.

Table 5 Grass production based on site class

Site class	Grass yield, t DM/ha	ETc mm	Green WF, m^3/t DM	Blue WF m^3/t DM	Total WF m^3/t DM
1	9.51	566	595		**595**
2	8.60	577	671		**671**
3	7.87	565	717		**717**
4	7.23	546	756		**756**
5	6.71	538	801		**801**
6	5.90	526	892		**892**
7	1.39	511	3,671		**3,671**

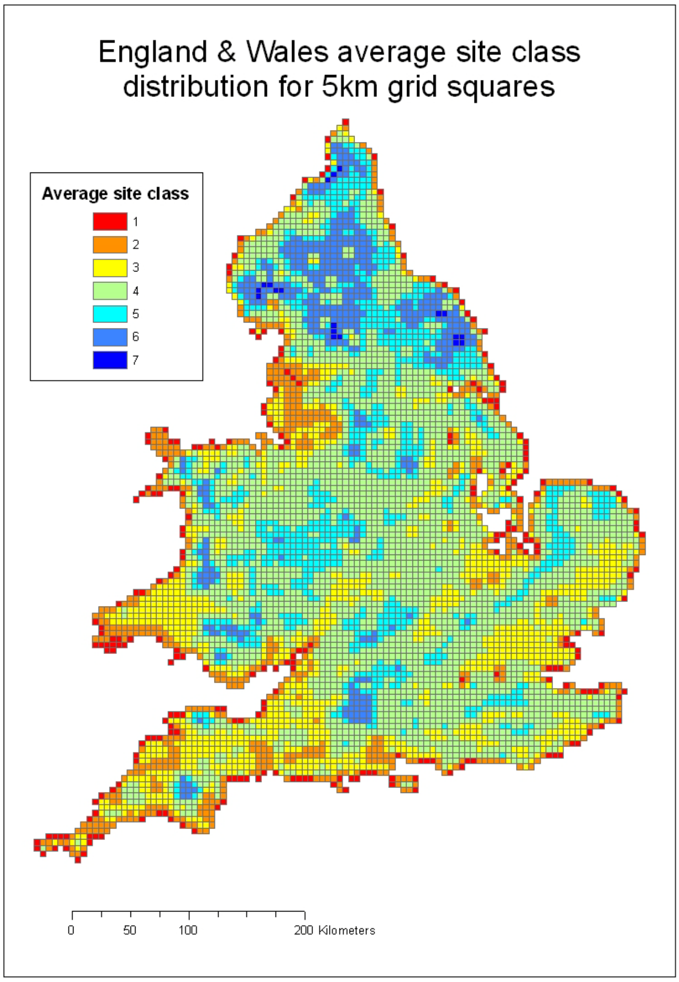

Figure 1 Average site class distribution in 5 km grid squares for England & Wales

Average grass water use is actually very similar across site classes, although for lower site classes the coefficient of variation (CoV) is just less than 10% compared with a CoV of 2% for site class 7.

The same process was followed for silage production, Table 6. The complete annual evapotranspiration values were used for silage on the basis that a silage field would be used solely for forage conservation. This is in contrast to annual arable crops in which only water evaporated during the growing season is accounted for. Fields may be used for both grazing and conservation in practice, but the model had to be parameterised in grazing and conservation parts.

Table 6 Green water use - Silage production

Site class	Silage yield, t DM/ha	ETc mm	Green WF m^3/t DM	Blue WF m^3/t DM	Total WF m^3/t DM
1	12.2	566	465		**465**
2	11.1	577	522		**522**
3	10.1	565	558		**558**
4	9.3	546	589		**589**
5	8.2	538	654		**654**

Grey Water Footprint

The potential requirement to dilute polluted water to below acceptable water quality standards could occur in several areas and depend on many variables and unknowns. Pollutants could include potential for de-oxygenation natural waters (e.g. from accidental slurry or silage effluent leaks), pesticide use or diffuse emissions of nutrients like phosphate and nitrate. These vary in the data quality, spatial variation, likely frequency of occurrence as well as the ability to attribute particular pollutants to beef or sheep (as opposed to dairy cattle, pigs or poultry). These were assessed for suitability given these criteria and all were excluded apart from nitrate leaching. It should be noted that these criteria may not be so appropriate for other agricultural activities (or industrial processes) or locations. The reasons for elimination follow:

- De-oxygenation from slurry or manure
  - Only general data on pollution incidence available and not really possible to attribute this to beef. Sheep should not be a cause as barely housed. Beef often kept with FYM systems, which cause less water pollution.
- De-oxygenation from silage effluent
  - As above on data, but also sheep are most likely to get baled silage and much beef too. Baled silage emits effluent, but being spread over the whole winter will cause fewer problems.
- Pesticides
  - Limited data availability and very hard to distinguish normal crop pesticides for feeds as opposed to other arable crops. The assumption had to be made that sheep dip could only be properly disposed of properly in an approved manner or else the pollution would be quite unacceptable.
- Phosphate
  - Limited variability in the LCA crop and grass model. In addition, the likely emission rate compared with nitrate suggests that nitrate is much more likely to be the first limiting pollutant.

As well as the above considerations, Hoekstra et al. (2009) give guidance on the calculating of the grey water footprint from agricultural activity and used nitrate leaching as the basis.

The Water Footprint Manual suggests that “the grey component in the water footprint of growing a crop or tree ($WF_{proc,grey}$, m^3/tonne) is calculated as the chemical application rate per hectare (AR, kg/ha) times the leaching fraction (α) divided by the maximum acceptable concentration (c_{max}, kg/m^3) minus the natural concentration for the pollutant considered (c_{nat}, kg/m^3) and then divided by the crop yield (Y, ton/ha).”

$$WF_{grey} = \frac{(AR \times \alpha)/(c_{max} - c_{nat})}{Y}$$

The nitrogen fertiliser application rate for each feed crop and grass/silage production was taken from the Cranfield LCA model and multiplied by the leaching fraction, which the Water Footprint Manual assumes to be uniformly 10%. The EU Drinking Water Directive sets a maximum level of nitrate in fresh water bodies as 50 mg/l NO_3, that is, 11.3 g/l Nitrogen (NO_3-N) and thus c_{max} was taken as 11.3 g/l or 0.0113 kg/m^3. The natural concentration of nitrates in fresh water bodies, c_{nat}, is assumed in the manual to be zero.

Table 7 Baseline water footprints including grey water footprint for nitrates

	Blue water use, m^3/t	Green water use, m^3/t	Grey water use, m^3/t	Total water footprint, m^3/t
Beef	66.7	14,900	2,690	17,657
Lamb	48.6	55,800	1,910	57,779

The above follows the Water Footprint Manual method, however, this interpretation could be misleading as it does not take into account that surplus rainfall (after evapotranspiration) could be available to dilute nitrates leached to freshwater bodies. In reality this would lead to a reduction in grey water requirement, Table 8.

The reduction for lamb is much greater than for beef because a much greater proportion of their diet is grazed grass. Fertiliser application is much greater for silage and feed crops, and thus leaching is assumed to be higher, therefore the surplus rainfall will have a smaller impact for animals with silage or concentrate-based diets than for those that are more grass-fed, where much of the grey water requirement is negated by the surplus rainfall.

Table 8 Grey water footprint, per tonne carcase meat, showing grey water required after rainfall

	Blue water use, m^3/t	Green water use, m^3/t	Grey water use, m^3/t	Total water footprint, m^3/t
Beef	66.7	14,900	2,050	17,017
Lamb	48.6	55,800	434	56,283

Total water footprint

Results were derived by using a modified version of the Cranfield LCA model (Williams et al., 2006), which had been improved for beef and lamb production as part of phase 1 of the EBLEX Roadmap (EBLEX, 2009). The Cranfield LCA Model takes a systems-based approach to modelling the environmental burdens of beef and lamb production to account for all inputs and outputs crossing a system boundary, in this case, from “cradle” to farm-gate. The model considers the different production systems for beef and lamb with the feed requirements of each production system calculated based on daily liveweight gain (DLWG), entry and slaughter weights. Blue water for drinking was calculated, as above, based on dry matter intake by an animal in each system. The model was adapted to incorporate the green water footprint of feed crops, grazing and silage and a blue water footprint value for drinking water and sheep dip. The green water component of concentrates was then derived based on the proportions of each crop required. The values derived for green water consumption per tonne of grass or feed crop were added to the model, which could then be used to calculate green water consumption, based on feed requirements for each system.

The model calculates results per tonne of carcase weight, (liveweight × killing out percentage) for different production systems, and allows proportion of production from each system to be defined. Thus the ‘National baseline’ results are representative of production in England and Wales Figures Figure 2 and 3, Table 9 and Table 10.

Blue, green and grey water footprint results can be added to give a total water footprint provided each is correctly calculated. For example, if feed crops are irrigated, this would be considered blue water, but this would lead to increased evapotranspiration. Therefore, whereas for this model, we have considered green water to be equal to evapotranspiration, if irrigation was used, this would need to be subtracted from the green water total.

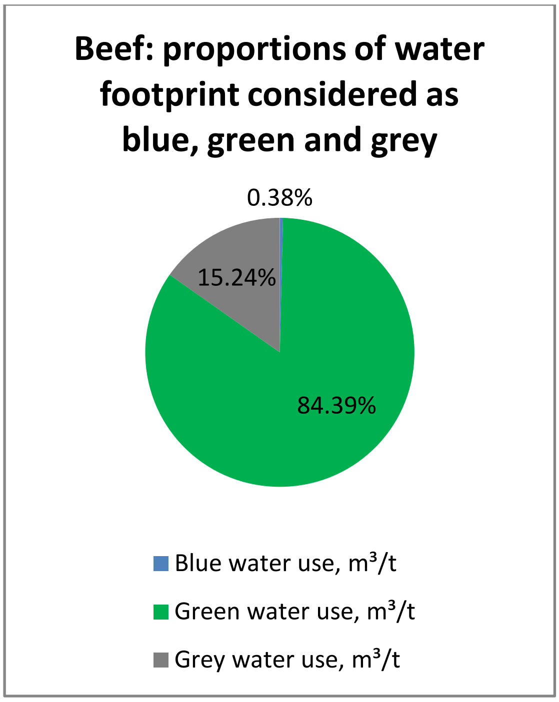

Figure 2 Total beef water footprint

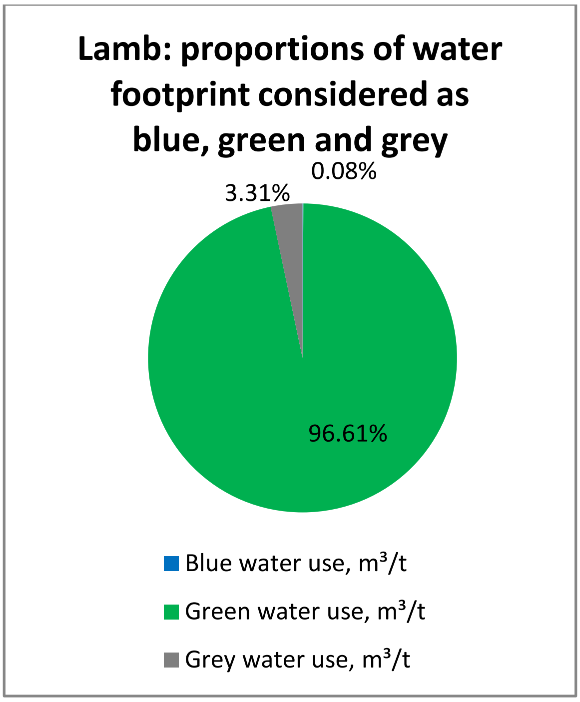

Figure 3 Total lamb water footprint water

Table 9 Total water footprints for beef systems in England per tonne of carcase weight

System	Blue water use, m^3/t	Green water use, m^3/t	Grey water use, m^3/t	Total water footprint, m^3/t
National Baseline	67	14,900	2,690	17,657
Sucklers (weighted average for suckler bred/finished beef)	85	20,400	3,270	23,755
Lowland sucklers (64% spring born)	78	15,600	3,490	19,168
Lowland spring sucklers	74	15,400	3,240	18,714
Lowland autumn sucklers	85	16,000	3,960	20,045
Upland sucklers (64% spring born)	81	12,800	3,300	16,181
Upland spring sucklers	76	11,600	2,930	14,606
Upland autumn sucklers	89	14,900	3,990	18,979
Hill sucklers	103	44,200	3,080	47,383
Dairy beef	45	8,150	1,980	10,175
Intensive dairy beef (cereal & silage fed)	37	7,930	2,100	10,067
Extensive dairy beef	48	8,240	1,920	10,208

Table 10 Total water footprints for lamb systems in England per tonne of carcase weight

System	Blue water use, m³/t	Green water use, m³/t	Grey water use, m³/t	Total water footprint, m³/t
National Baseline	49	55,800	1,910	57,759
Hill lambs	85	135,000	205	135,290
Upland lambs	40	24,700	2,600	27,340
Lowland lambs	31	21,800	2,550	24,381
Early lambs	25	23,200	3,440	26,665

It is evident that water consumed in the production of beef and lamb is almost entirely green water required for feed crop and grass production,

Figure 4. Blue water consumption is limited to drinking water and sheep dip. Suckler beef has a greater water footprint than dairy beef, due to water consumed by the suckler cow (both in feed and drinking water, but mainly embedded or "virtual" water in feed). Hill systems have a much higher water use because grass yields are significantly lower and thus green water footprints are much greater per tonne of grass required. This is ironic given the higher rainfall in most hilly areas.

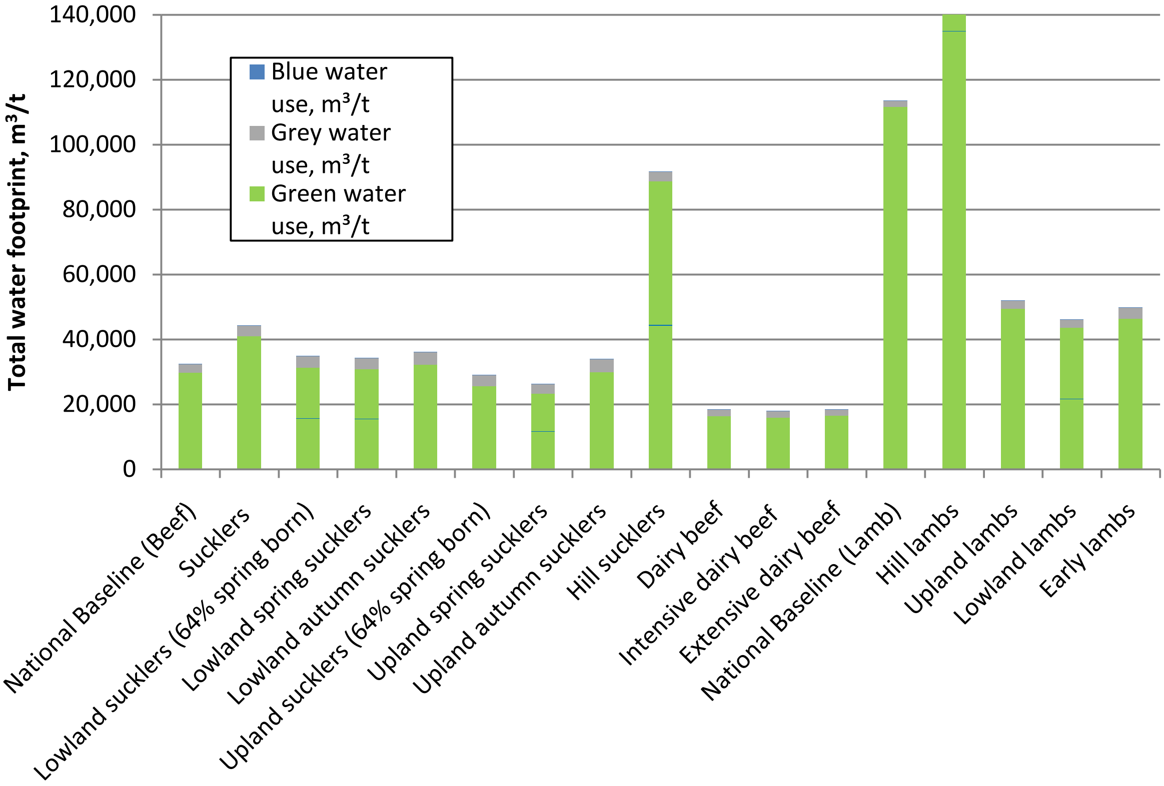

Figure 4 Comparison of blue, green and grey water footprint (per t carcass weight) results for beef and lamb systems

Comparison with other studies is difficult because of differences in the methods used. As with Life Cycle Assessment (LCA), it should be remembered that other studies may have different boundary conditions and assumptions.

The Water Footprint Network widely quote the global average water footprint for beef as being 15,500 L/kg (or m^3/t). Hoekstra and Chapagain (2008) have produced statistics for the water footprints of crop and livestock products for selected countries. For the UK, it offers a value of 7,952 m^3/t for bovine carcases; about 45% of that in the present study, but we know that our values includes breeding overheads and domestic finishing systems. Their values are based on international datasets rather than specific data for the UK. The dataset provides values for several hundred crop and livestock commodities for 65 countries, which suggests that the values have not been individually calculated and will be based on average yields using the FAO CROPWAT method (2009) to estimate effective monthly rainfall. As explained in Hess (2010), many studies use the CROPWAT v8.0 model, and within this, although it offers several alternative methods, the USDA SCS method has generally been used due to its simplicity. Hess (2010) further explains that this method estimates effective rainfall, based on the original USDA SCS model that was calibrated using US hydrological data. Although this has been shown to perform well in well-drained soils in the US, the effective rainfall method is less suited to UK soils where crops can draw on stored soil water as well as summer rainfall. This leads to an underestimate of green water consumption, in some cases giving an estimate of green water footprint only 40% of that derived from a water balance study (Hess, 2010). Peters et al. (2010) suggest that in many previous studies rain water has generally been excluded for reasons of data quality, with the focus being on water from surface and groundwater storage, leading to some very low estimates for Australian beef such as Foran et al.'s value of 209 L/kg beef (2005, cited in Peters et al. 2010). This is still three times higher than the blue water footprint for English beef, however, as so few crops are irrigated.

Importance of the water footprint

Is the Green Water Footprint important?

The Water Footprint Network (WFN, 2010) argues that the green water footprint is a measure of mankind's appropriation of water for food production and therefore that water is not available for nature. They argue that the green water footprint correctly reflects the "cost" of a crop in terms of its total water use. However, the "cost" of the water footprint should reflect the alternative uses to which that water could have been put, that is, the opportunity cost. In the case of blue water, the opportunity cost is clear - water that is abstracted from a river or groundwater for irrigation is not available for other downstream used (such as domestic water use, industry or sustaining environmental flows), therefore, abstracting blue water has a significant cost to society. Rain water used to grow grass or crops cannot be allocated to other uses (unless rain is artificially "harvested" and used to substitute for blue water). If grass were not grazed, or rainfed crops were not grown on the land, there would still be evaporation and transpiration from the land. Indeed, if the land were forested, the evapotranspiration would be even higher, because deep rooted plants transpire more than shallow rooted ones.

Some have argued that a more realistic estimate of the "cost" of green water can be obtained by comparing the green water use of the crop with that of "natural vegetation". SAB Miller (2009) for example, in a study of the water footprint of the ingredients for beer making, defined the concept of "net green water" as the difference between the crop evaporation and the natural evaporation. Whilst this opens up a debate about what is "natural vegetation" in a country like England, in practice, the annual evaporation from natural vegetation is similar to that of grass and rainfed agricultural crops. In the case of woodlands, it may even be higher (suggesting that cropping may have a negative net green water footprint!). As a result, the net green water footprint of rainfed agriculture in England would be close to zero.

It is clear that green water has a lower opportunity cost than blue water, and in many cases no opportunity cost at all. Some have suggested that green water "could be considered a 'gift'" Chapagain and Orr (2009, p1227).

This study has demonstrated that the total water footprint of English lamb and beef (m^3/kg) is of a similar order to estimates from other countries, however, the overwhelming dominance of green water in the total figure demonstrates that, compared to livestock production systems that rely on irrigated feed, the hydrological impact of English meat production is very small.

Results show an increased green water footprint for hill sheep and beef. However, as discussed, these animals will be primarily fed on grass in upland and hill areas where the rainfall is much higher and thus the rainfall surplus (after ET) will be much greater than in other areas also. It could therefore be said that that these areas are not reducing water flow to rivers and streams any more than other areas. Additionally, if these areas were left ungrazed, natural vegetation would still grow, consuming the same if not greater quantity of green water.

Furthermore, regions with high site classes are generally upland or hill areas with poor growing potential and would therefore be unsuitable for many other purposes such as arable production. If the grassland in such areas were replaced with forestry, this would have a much higher evapotranspiration rate and therefore greater "green" water footprint, therefore diverting more water from surface and groundwater resources within the catchment (Hess, 2010).

Maps

Rainfall and evapotranspiration point data for England and Wales were mapped onto a 5 km grid and average values for each grid square were calculated, , Figure 6. Similarly an average site class value for each grid square was calculated, Figure 1.

It was then possible to combine these data based on grid square reference to derive the average rainfall surplus per site class and map these, Figure 7. Furthermore, using the average grass DM yields, Table 5, the rainfall surplus per tonne of grass dry matter production could be calculated and mapped, Figure 8. These clearly show that even in the driest areas, there is still a significant amount of rainfall above what is required for grass production. For areas with higher site classes, where grass yield is much lower than for other areas, by definition these have higher rainfall, and thus high surplus rainfall per tonne DM grass coincides with areas of high site class.

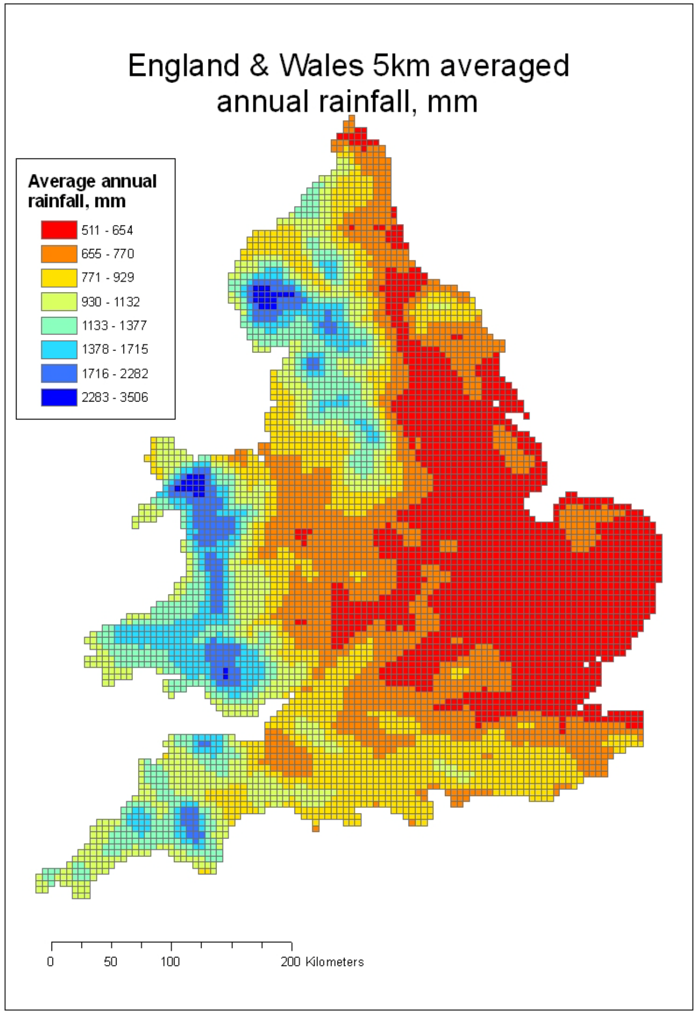

Figure 5 Average annual rainfall for England & Wales

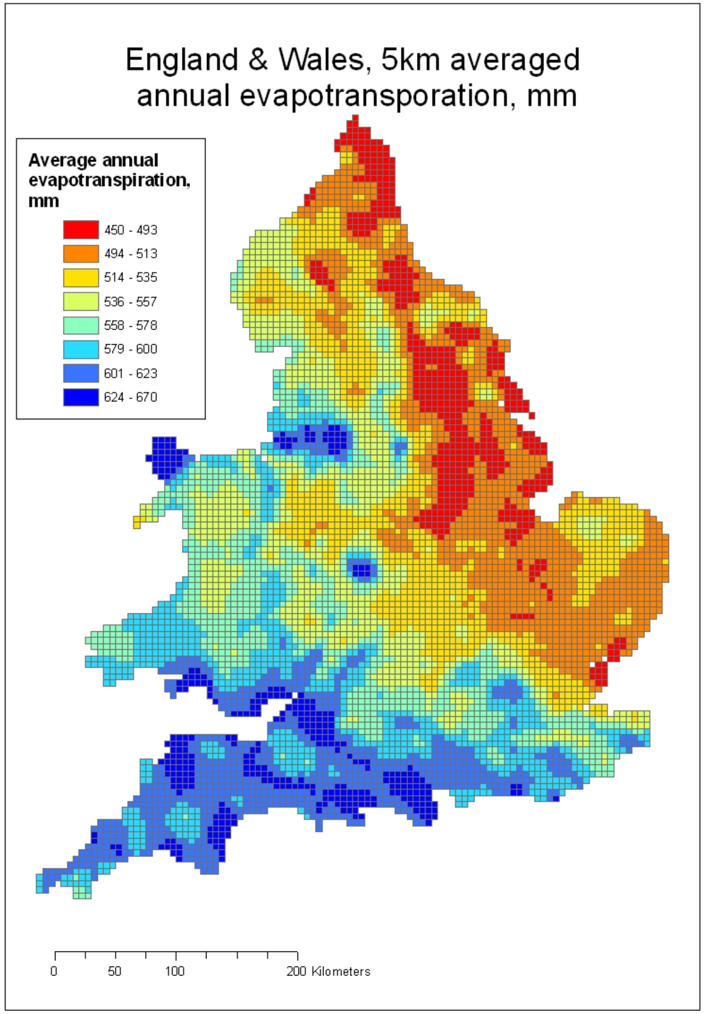

Figure 6 Average annual evapotranspiration for England and Wales

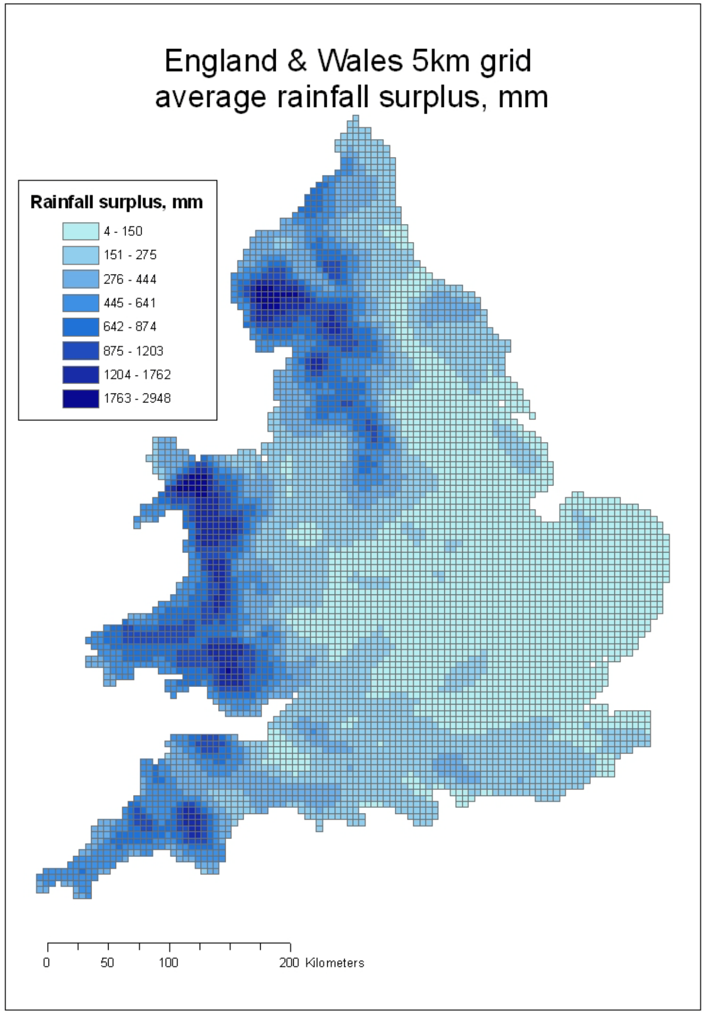

Figure 7: Average surplus rainfall, mm per 5 km grid square

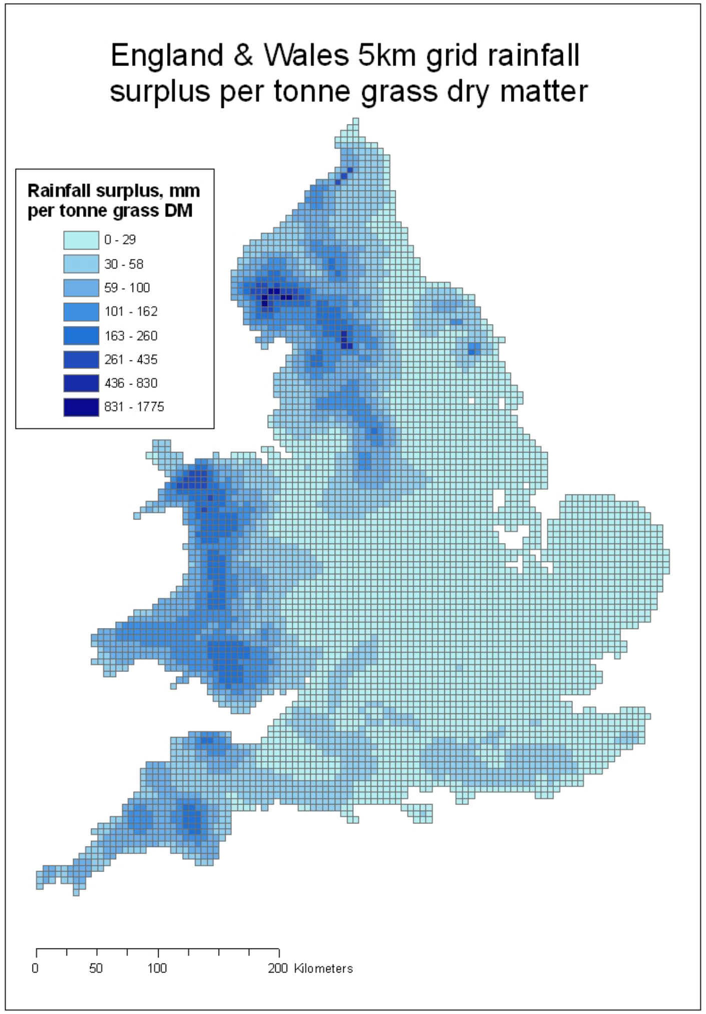

Figure 8: Average surplus rainfall, mm per tonne DM grass yield for each site class

Uncertainty

Formal uncertainty analysis is difficult due to the lack of published uncertainty values for most sources. Errors may arise in two forms, both from primary data, i.e. values that can be measured, for example natural variation in animal drinking water consumption, and in secondary form such as data taken from a sources or simulation models, for example leaching factors for grey water calculation. It is estimated that the coefficient of variation (CoV, defined in the Glossary) for various sources would be in the following order of magnitude:

Drinking water requirements: 5-10%

Evapotranspiration of crops and grass: 10%

Crop yields: 5%

Feed conversion and general productivity: 15%

Grey water calculations: 30%

The error associated with grey water requirements is mostly due to the assumptions made in the method, such as assuming a blanket figure of 10% leaching fraction.

Whatever the overall error is, the errors in each part of the systems modelled are highly correlated so that comparisons between systems have much lower errors than between the measurements of different research groups. An overall estimate of error for the total water footprint is about 30% (as CoV).

Perspectives & Recommendations

For English beef and lamb production, the overwhelming majority of water consumption is green water embedded in grass and feed crops. Analysis of grey water use for dilution of nitrates leached from crops and grassland shows that this is also very small in comparison to green water use, particularly if some of this function can be performed by surplus rainfall.

The total result for beef at 17,700 m^3/t is very close to the Water Footprint Network value of 16,000 L/kg (equivalent to m^3/t), however when the breakdown of results into green, blue and potentially grey water consumption is considered, it is clear that describing a water footprint in terms of a single total value can be misleading. Without this breakdown there is no distinction between rainfall and irrigation supply, which means that UK beef production may appear similar in impact to countries such as the US where irrigation of feed crops is dominant. In reality, even when grey water is considered, more than 80% of water consumption for beef and lamb production in the UK is rainfall.

Furthermore, because blue, green and grey water footprints are additive and have no weighting system, neither separate or aggregated water footprint results give an indication of relative importance of the type or water, or geographical importance of the water. This highlights part of the problem of looking at the total water consumption rather than the impact of that water consumption. When presented with the main values of green and blue water consumption, a user is given no idea of the context or impact of this water use, for example, whether the water was abstracted from a water-stressed catchment, what conflicting uses there may be for the water.

As discussed, if grassland was not grazed, or feed crops not produced, there would still be evapotranspiration from vegetation on the land, indeed, if land were used for forestry, evapotranspiration would most likely be greater than for grass or crops. Thus the main areas of guidance for farmers would be with respect to blue and grey water use. This could include:

- Water recycling and rainwater harvesting to reduce blue water use.
- Good management of pipes and drinkers to ensure no leakages.
- Better grassland management - more refined with respect to nitrates in order to reduce grey water requirements.

The last two are ones that are clearly synergistic with other environmental and economic goals. So that cost-incurring barriers towards improvement should not obstruct the industry.

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Glossary

AOD - Above Ordnance Datum (height relative to the average sea level at Newlyn, Cornwall UK)

CoV – Coefficient of Variation: defined as the ratio of the standard deviation (σ) to the mean (μ):

$$c_v = \frac{\sigma}{\mu}$$

DM – Dry Matter

ET – Evapotranspiration

ETa – Actual Evapotranspiration

ETc – Average seasonal crop evapotranspiration

ETo – Reference evapotranspiration (i.e. a theoretical value for the rate of evapotranspiration from a hypothetical reference crop in which no restriction though drought or disease occurs)

FW – Fresh weight

WF – Water Footprint

Appendix 1: Feed crop data

Table 11 Climate stations used for the estimation of the water footprint of wheat and barley.

Station	Crops	Latitude	Longitude	From	To	Altitude	Average annual	
						(m AOD*)	Rainfall (mm/y)	ETo (mm/y)
Brooms Barn	W,B, OSR, SB	52.15 N	0.34 E	1964	1990	75	588	585
Silsoe	W,B, OSR	52.01 °N	0.41 °W	1963	1990	59	547	541
Terrington St. Clement	W,B, OSR, SB	52.75 N	0.29 E	1963	1990	3	587	564
Gleadthorpe	SB	53.22 °N	1.12 W	1970	1990	60	628	470

*see Glossary

Table 12 Climate stations used for the estimation of the water footprint of soya.

Country	Station	Lat	Long°	Planting date	Season length (days)	Rain†, mm	ETc†, mm
Argentina	Cordoba	-31.43°S	64.25°W	01-Dec	140	523	595
Brazil	Goias	-15.91°S	50.13°W	15-Nov	140	1331	454

† total for the growing season of 140 days.

Table 13 Estimated blue and green water footprint of sugar beet.

Source		%	ETg (mm)	ETb (mm)	Yield t FW/ha	WFg	WFb	WFb m3/t
E England	Rainfed	70%	534		63.5	84		**58**
E Midlands	Rainfed	24%	453		63.5	71		**17**
E England	Irrigated	4%	461	126	63.5	73	20	**4**
E Midlands	Irrigated	2%	384	100	63.5	61	16	**1**
Weighted average			**509**	**7**	**63.5**	**80**	**1**	**81**

Appendix 2: Sensitivities

Maps

The maps shown use a classification system known as ‘Natural Breaks’, which is the default used by the mapping software. If other classification methods are used, a different image can be portrayed, however all show the effect of high rainfall in western areas at high altitude, such as Dartmoor and the Lake District, with East Anglia consistently the driest region, with least rainfall surplus after evapotranspiration.

For completeness examples are given using the other classification systems, Figure 9, Figure 10.

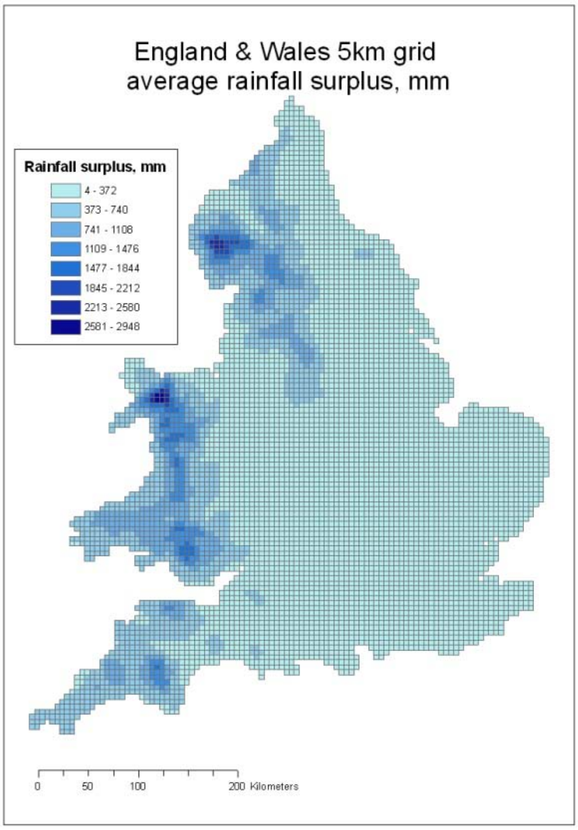

Figure 9 Rainfall surplus map using equal interval breaks

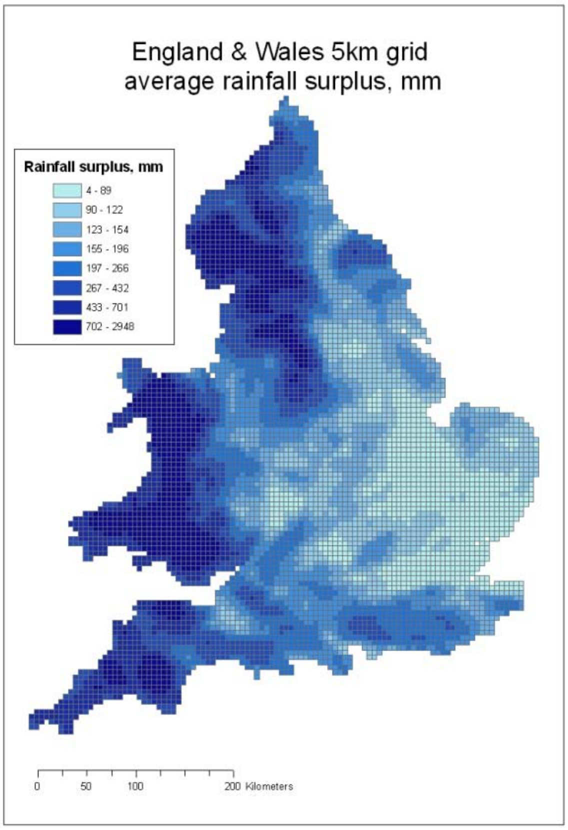

Figure 10 Rainfall surplus map using 'quantile' divisions with the same number of data values in each interval

Soya

Soya meal for concentrate feed is usually imported from either Argentina or Brazil and thus growing conditions will be most different from domestically or European-produced feed crops. The exact quantities used are uncertain and may vary between production systems and farms. To test for this sensitivity, we removed soya meal from the concentrate composition within the Cranfield LCA model and replaced it with the same quantity of rape meal, Table 14.

Table 14 Results of soya meal in concentrates sensitivity analysis

	Soya sensitivity	Blue water use, m^3/t	Green water use, m^3/t	Grey water use, m^3/t	Total water footprint, m^3/t
Beef (national baseline figure)	5.5% soya in concentrate feed	67	14,900	2,690	17,660
Beef	No soya meal used	67	14,600	27,40	17,410
Lamb (national baseline figure)	5.5% soya in concentrate feed	49	55,800	1,910	57,760
Lamb	No soya meal used	49	55,600	1,940	57,590

This analysis shows that despite the higher green water footprint of soya, due to its relatively low yield, for the proportions currently used it does not make a significant difference to the total water footprint of English beef and lamb production. Furthermore, the water required is green rather than blue water that has been abstracted from stored water and thus has a much lower opportunity cost than if the crop were irrigated.

The water footprint of English beef and lamb production

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