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1 **Water footprinting of pasture based farms; Beef and Sheep**

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37 Short Title: Water footprint of beef and sheep farms

38 **Abstract**

39 In the context of water use for agricultural production, water footprints have
40 become an important sustainability indicator. To understand better the water demand
41 for beef and sheep meat produced on pasture based systems, a water footprint of
42 individual farms is required. The main objective of this study was to determine the
43 primary contributors to freshwater consumption up to the farm gate expressed as a
44 volumetric water footprint (WF) and associated impacts for the production of one kg
45 of beef and one kg of sheep meat from a selection of pasture based farms for two
46 consecutive years, 2014 and 2015. The water footprint included green water, from
47 the consumption of soil moisture due to evapotranspiration, and blue water, from the
48 consumption of ground and surface waters. The impact of freshwater consumption
49 on global water stress from the production of beef and sheep meat in Ireland was
50 also computed. The average WF of the beef farms was 8 391 L/kg carcass weight
51 (CW) of which 8 222 L/kg CW was green water and 169 L/kg CW was blue water;
52 water for the production of pasture (including silage and grass) contributed 88% to
53 the WF, concentrate production, 10% and on-farm water use, 1%. The average
54 stress-weighted WF of beef was 91 L H₂O eq/kg CW, implying that each kg of beef
55 produced in Ireland contributed to freshwater scarcity equivalent to the consumption
56 of 91 L of freshwater by an average world citizen. The average WF of the sheep
57 farms was 7 672 L/kg CW of which 7 635 L/kg CW was green water and 37 L/kg CW
58 was blue water; water for the production of pasture contributed 87% to the WF,
59 concentrate production, 12% and on-farm water use, 1%. The average stress-
60 weighted WF was 2 L H₂O eq/kg CW for sheep. This study also evaluated the
61 sustainability of recent intensification initiatives in Ireland and found that increases in

62 productivity were supported through an increase in green water use and higher grass
63 yields per hectare on both beef and sheep farms.

64

65 **Keywords;** grass, freshwater consumption, beef production, sheep production
66 sustainable intensification.

67

68 **Implications**

69 To understand better the water demand for pasture based beef and sheep
70 production systems, a water footprint of individual farms is required. The main
71 objective of this study was to determine the primary contributors to freshwater
72 consumption through a volumetric water footprint (WF) and calculation of associated
73 impacts for the production of one kg of beef and sheep meat on a selection of Irish,
74 pasture based beef and sheep farms for two consecutive years, 2014 and 2015.
75 The average WF of the beef farms was 8 391 L/kg carcass weight (CW) of which
76 98% was green water and 2%, blue water. The average WF of the sheep farms was
77 7 672 L/kg carcass weight of which 99% was green water and 1%, blue water.
78 This study presented the first WF assessment of beef and sheep farms in Ireland
79 using farm specific data which is an important addition to WF literature. The data
80 presented in this paper can be used to assess the demands of freshwater as a result
81 of beef and sheep production on pasture based systems.

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86

87 **Introduction**

88 The beef and sheep industries are significant components of the Irish agri-
89 food sector. Beef exports accounted for 22% or a value of €2.27bn in exports in
90 2015, while the sheep meat industry accounted for €218 million. The majority of beef
91 (>90%) and sheep (72%) produced in Ireland is exported to the UK and continental
92 Europe (BordBia, 2015a). Ireland is the largest net exporter of beef in the European
93 Union (EU) (fifth largest in the world) and the largest net exporter of sheep meat in
94 the northern hemisphere (BordBia, 2015a).

95 Some 90% of beef produced in Ireland is produced under Origin Green, a
96 sustainability program that operates on a national scale, which includes farm to fork
97 traceability and documentation of medicine use, etc. (BordBia, 2015b). This scheme
98 has recently been updated to integrate sheep farming through the Sustainable Beef
99 & Lamb Assurance Scheme (SBLAS) launched in 2016 (BordBia, 2015b). This
100 program's carbon footprinting method is independently accredited at farm level by
101 the Carbon Trust (PAS, 2008). The carbon footprint of Irish beef (Casey and Holden,
102 2006a) and sheep (O'Brien *et al.*, 2016) production has been quantified, however a
103 detailed water footprint (WF) of these systems using farm specific data is missing
104 which is becoming important for environmentally conscious consumers (Grunert *et*
105 *al.*, 2014).

106 Water footprints have been used to describe and assess water use in agricultural
107 production systems such as dairy and meat production (Mekonnen and Hoekstra,
108 2010). A volumetric water footprint includes the sum of consumption of soil moisture
109 due to evapotranspiration of precipitation (green water), and consumption of ground
110 and surface waters (blue water). While green and blue water represent consumed
111 water, grey water represents an emission. It has been argued, therefore, that grey

112 water can be better represented in a life cycle assessment (LCA) impact factor
113 (Pfister *et al.*, 2009) such as eutrophication and so was excluded from this analysis.
114 The division into green and blue water sources describes two different pathways of
115 water use in agricultural systems. Partitioning between green and blue water is
116 useful as it can also highlight differences in production systems for a similar output
117 (Rockström *et al.*, 2010).

118 The volumetric water footprints and impacts of water use for beef and sheep
119 production systems in the UK, Australia and New Zealand have been addressed in
120 the literature (Chatterton, 2010, Ridoutt *et al.*, 2012a, Zonderland-Thomassen *et al.*,
121 2014, Wiedemann *et al.*, 2016a, Wiedemann *et al.*, 2016b), however no current
122 literature exists addressing the water demands of Irish, pasture based beef and
123 sheep production systems using farm specific data. It is important for the
124 marketability of Irish beef and sheep meat to have access to information on the
125 freshwater demand of these production systems. This will enable policy makers to
126 make meaningful comparisons, understand the potential for reducing the WF of beef
127 and sheep production systems and potentially achieve a comparative advantage
128 over similar livestock products from other countries. Therefore, a need was identified
129 to assess fresh water use and potential environmental impacts related to water use
130 associated with both beef and sheep production systems in Ireland.

131 The main objective of this study therefore, was to determine the primary contributors
132 to freshwater consumption up to the farm gate expressed as a volumetric WF and
133 associated impacts for the production of one kg of beef and sheep meat on a
134 selection of Irish, pasture based farms for two consecutive years, 2014 and 2015.
135 Ridoutt *et al.* (2012b) stressed that while a volumetric WF is useful in highlighting the
136 intrinsic role of freshwater resources in livestock production, it is not correlated with

137 the environmental impact of freshwater use. Changes in water availability due to
138 consumption of fresh water resources should also be included. In line with the recent
139 ISO WF standards (ISO, 2014,), the WF should indicate potential environmental
140 impacts related to water use. Water scarcity as a mid-point impact indicator of
141 freshwater use can be quantified using the method developed by Pfister *et al.*
142 (2009). To account for the impacts of water use, we have also included in our
143 analysis, an LCA mid-point indicator, i.e., the stress-weighted WF, to account for the
144 environmental impact of blue water use (Pfister *et al.* 2009).

145 Food Harvest 2020 and the subsequent Food Wise 2025 are national plans
146 for intensification of agriculture which have identified opportunities to increase the
147 economic output of the beef and sheep sectors through sustainable intensification
148 (DAFM, 2010 and 2015). These agricultural intensification measures are expected to
149 lead to an increase of €1.6 bn in output (DAFM, 2010). As a result of these policies
150 the sustainability of forecasted intensification of beef and sheep farms was assessed
151 from a water consumption perspective.

152

153 **Materials & Methods**

154 *System boundaries*

155 Ten commercial beef farms and six commercial lowland, seasonal grazing
156 sheep farms were selected from the Teagasc advisory database, referred to as study
157 farms. Data was collected from these farms for two years (2014 and 2015). The beef
158 farms carried an average of 117 LU while the sheep farms carried 86 LU. Selection
159 criteria included availability of herd and production data and willingness of the farmer
160 to collect and maintain data accurately. The system boundary was cradle-to-farm
161 gate. Freshwater use required for the cultivation of crops for concentrate feed, on-

162 farm cultivation of grass or fodder and water requirements for animal husbandry and
163 farm maintenance and was expressed per kg CW output (carcass weight). Water
164 use related to energy and fertilizer production was not included in this study.

165

166 *Data collection and management*

167 Data on farm infrastructure and animal production were gathered by means of
168 a survey. This included information relating to on-farm water sources (private well/
169 local government supply), stock numbers, concentrate sources and production data.
170 Water meters were also installed on each farm to record water volumes (m³)
171 throughout the farm network. Domestic water consumption was measured separately
172 and subtracted from the total water supply to determine water supply to the farm
173 enterprise only. Water volumes were measured monthly via an online survey with the
174 farmers recording each water meter reading and inputting the data to the online
175 system. Data on farm imports such as concentrate fed and forages fed were also
176 collected monthly. Animal sales and carcass weight data were gathered from each
177 farmer. Concentrate feed composition and ingredient origin was gathered from local
178 feed mills and previous literature (Casey and Holden, 2006b, O'Brien *et al.*, 2016).
179 These ingredients are listed in Table 1.

180 All data were exported to spreadsheets and subsequently used to compute the WF
181 of individual farms. The average, maximum and minimum of the production
182 parameters and WF for each year was computed.

183

184 *Allocation method*

185 Allocation method refers to the portioning of environmental impacts within a
186 multifunctional process. Five sheep farmers also kept some beef animals, therefore

187 in order to separate the 'on-farm' water use between the sheep and beef enterprises,
188 physical allocation was used between the sheep (55%) and beef outputs (45%),
189 which was based on the ratio of sheep:beef livestock units (LU) on the farms during
190 the period of the study. The LU system is a reference unit which facilitates the
191 grouping of livestock from various species and age through the use of specific
192 coefficients established from the nutritional requirements of each type of animal. One
193 LU is equivalent to one adult dairy cow. To account for the co-production of sheep
194 meat (97%) and wool (3%), economic allocation was used. Previous studies have
195 used economic allocation to separate products of crop systems for concentrate
196 production (O'Brien et al., 2016, Murphy *et al.*, 2017), thus this method was used to
197 allocate the environmental impacts of concentrate co-products.

198

199 *Water required for crop cultivation*

200 Green and blue water consumption required during crop growth was
201 calculated using the method described by Murphy *et al.* (2017). Fresh water required
202 to grow a crop can originate from precipitation and soil water (green water) or, in the
203 case where water demand exceeds precipitation, from irrigation (blue water). All
204 irrigation water was assumed to be consumptive, implying that losses in the irrigation
205 system did not return to the same catchment, representing a worst-case scenario.
206 'Consumed' water refers to loss of water when it is evaporated, incorporated into a
207 product or returned to another catchment.

208 To assess the freshwater requirements for growth for each crop input
209 (concentrates, forages and grass), the evapotranspiration (ET) was computed based
210 on climate data, soil type and actual yield data. First, AQUASTAT, developed by the
211 FAO was used to compute the reference ET (ET_o) for each crop location. Second,

212 the potential ET (ET_p) over a crops growing period, assuming maximum soil water
213 availability was derived using the crop co-efficient (K_c [t]) and the reference ET_o on
214 AQUASTAT using the Penman-Montieth equation (Allen *et al.*, 1998). Third, results
215 from AQUASTAT were then used to derive the rainfed ET of the crop (ET_{rf}). ET_{rf} is
216 an estimate for the volume of water evapotranspired (green water) of a crop over the
217 growth period. Fourth, actual crop yields taken from the FAO (2014) were then used
218 to quantify the consumption of rainwater (green) and irrigation (blue) water in litres
219 per kg of dry matter. The ET from the actual yield of a crop (ET_a , mm/ha) was then
220 derived from the relationship between water supply and crop yield described by
221 Doorenbos and Kassam (1979). Irrigation was assumed to be absent where $ET_a \leq$
222 ET_{rf} . When $ET_a \geq ET_{rf}$, irrigation volumes were calculated by:

$$223 \quad \text{Irrigation volume} = (ET_a - ET_{rf}) / I_{eff} \quad (1)$$

224 I_{eff} is the irrigation efficiency. A default efficiency of 0.7 was assumed for all crops
225 (Allen *et al.*, 1998).

226

227 *Grass and silage utilisation*

228 The dry matter (DM) intake of grass was estimated according to the net
229 energy (NE) required for animal growth and maintenance (Jarrige, 1989). Animal
230 weight, growth rates, activity, pregnancy and feed digestibility were based on the
231 surveys collected from the farmers and O'Mara (1996). The quantity of grass and
232 silage fed to the animals (kg DM) was then calculated by the difference between the
233 NE provided by external supplements (concentrates and imported forages) and the
234 NE demands for animal growth and maintenance. The WF of the grass grown
235 included a utilisation rate of 85% on beef and sheep pasture systems (O'Donovan,
236 2011a, Creighton and Kelly, 2014) and a residual rate of 15%.

237

238 *Water stress index*

239 The water stress index (WSI) is a mid-point indicator used to assess the
240 relative impact of freshwater consumption. The impact of freshwater deprivation to
241 the global freshwater system applies to blue water only (Pfister *et al.*, 2009). This
242 method can be applied at the country, region and watershed level. To calculate the
243 stress-weighted WF, all total volumes of blue water in each region of consumption
244 were multiplied by the specific regional WSI and summed across the supply chain of
245 the livestock system. To assess the global impact of freshwater use, the stress-
246 weighted WF was normalised by dividing it by the global average WSI, resulting in a
247 quantitative comparison of the pressure exerted from freshwater use through the
248 consumption of a product, relative to the impact of consuming 1kg of water across
249 the globe (Ridoutt and Pfister, 2010). The severity of water scarcity of a water shed
250 is ranked as follows: $WSI < 0.1$ low; $0.1 \leq WSI < 0.5$ moderate; $0.5 \leq WSI < 0.9$
251 severe and $WSI > 0.9$ extreme (Pfister *et al.*, 2009). The unit of water stress, L H₂O-
252 eq (H₂O equivalent), implies that each kg produced contributed to fresh water
253 scarcity, equivalent to the consumption of fresh water by an average world citizen.

254

255 *Water use through intensification*

256 The Food Harvest 2020 policy targets a 40% and 20% increase in the value of
257 the beef and sheep sector, respectively, by the year 2020 from the reference years
258 2007-2009 (DAFM, 2010). By 2015, through intensification initiatives, Irish beef
259 exports amounted to 524 000 tonnes worth €2.27 billion, representing a 39%
260 increase in value (DAFM, 2015). The sheep sector increased by 19% to €204 million
261 compared to 2010 Food Harvest baseline figures (BordBia, 2015a). The Food Wise

262 2025 report believes that further growth is achievable by 2025 through an 85%
263 increase in the value of agri-food exports €19 billion (DAFM, 2015); but to date, no
264 specific targets for growth have been outlined for production sectors. In order to
265 maintain sustainable growth in livestock production, an evaluation of the changes in
266 freshwater demands due to intensification is necessary.

267 To carry out this evaluation, production parameters on specialised beef and
268 sheep farms were taken from baseline production data representative of the time
269 period 2007-2009. These data were used to calculate the change in demand for
270 freshwater up to 2015. As grass made up the largest proportion of DM intake on beef
271 (89%) and sheep (91%) farms in this study and the largest portion of total water
272 demand (88%, beef; 87%, sheep), only changes in the water demand for grass
273 growth as a result of intensification were assessed. Data on national herd size on
274 specialised beef and sheep farms were gathered from the agricultural census (CSO,
275 2012) for 2010 and from the Central Statistics Office for 2015 (CSO, 2015). Average
276 national grass yields were derived from the National Farm Survey in 2010 (Hennessy
277 *et al.*, 2010) and from PastureBase for drystock (beef and sheep) farms in 2015
278 (Griffith *et al.*, 2014). Long term average rainfall for the last 30 years was used to
279 avoid yearly variation and represent the 'normal' climate of Ireland (Walsh, 2012).
280 Water required for the growth of grass was calculated as described in the previous
281 sections.

282

283

284

285

286

287 **Results**

288 *General farm characteristics*

289 Table 2 (Supplementary Table S1 and S2) summarises the range of inputs
290 and average production details of the study farms over two years (2014 and 2015).
291 The average beef study farm size was 50 ha and produced 24 058 kg CW output.
292 The average grass yield on the beef farms was 8 644 kgDM / ha. The average sheep
293 farm size was 42 ha and produced 14 550 kg CW. The average grass yield on the
294 sheep farms was 6 779 kgDM / ha. The study farms had greater production
295 parameters than national average production figures; national average CW output
296 per farm was 10 493 kg on beef farms and 9 450 kg CW on sheep farms (CSO,
297 2012). The production figures for study farms were also larger than typical
298 'intensive' beef and sheep production systems analysed in the literature in the recent
299 past, (Casey and Holden, 2006a, O'Brien *et al.*, 2016). The study farms therefore,
300 represent larger than average beef and sheep farms. This is representative of the
301 improvements in productivity on farms that are expected as a result of the Food
302 Harvest and Food Wise intensification policies (DAFM, 2010 and 2015).

303

304 *Green and blue water use*

305 e SD = Standard deviation.

306

307

308 Table 3 (Supplementary Table S3 and S4) summarises the total green water
309 footprint (GWF), total blue water footprint (BWF) and stress-weighted WF for the on-
310 farm and concentrate BWF for the study farms. Concentrate GWF and BWF and
311 grass GWF are also presented. The sum of the total GWF and total BWF gives the
312 total volumetric WF for each farm which is also indicated.

313

314 *Total volumetric water footprint*

315 The average total volumetric WF of the beef study farms was 8 391 L/kg CW
316 (range 4 993 L/kg CW to 11 130 L/kg CW). The total GWF of the beef systems made
317 up 98% of the Total WF with the total BWF making up the remaining 2%.

318 The average total volumetric WF of the six sheep study farms was 7 672 L/kg
319 CW, (range 5 017 L/kg CW to 9 933 L/kg CW). The GW input into the sheep systems
320 made up 99% of the WF with BW making up the remaining 1%.

321

322 *On-farm blue water footprint*

323 On-farm BWF refers to the volume of water used for farm maintenance and
324 water consumed by livestock. In all cases this water was sourced from a private well
325 and therefore, included blue water only. The average beef on-farm BWF was 64 L/kg
326 CW (range 19 L/kg CW to 173 L/kg CW). The on-farm BWF made up 38% of the
327 total beef BWF with the remaining BWF consumed for concentrate production.

328 The average sheep on-farm BWF was 37 L/kg CW (range 22 L/kg CW to 65
329 L/kg CW). The sheep on-farm BWF made up 99% of the total BWF with the
330 remaining 1% attributed to concentrate production.

331

332 *Concentrate water footprint*

333 The average volumetric beef WF for concentrate production (sum of green
334 and blue concentrate WF) was 921L/kg CW (range 206 L/kg CW to 2 079 L/kg CW).
335 Green water made up 89% of the water demand in concentrate production. Less
336 than 1% of the total beef WF was for BW use in beef concentrate production,

337 associated with the irrigation of crops such as sugarcane, originating in Cuba for the
338 production of molasses, and beet pulp from Germany.

339 The average volumetric WF for sheep concentrate production was 936 L/kg
340 CW, (range, 127 L/kg CW to 1 765L/kg CW). Almost all of the total water consumed
341 for concentrate production on sheep study farms was attributed to green water use,
342 while only 1% was attributed to blue water.

343

344 *Grass water footprint*

345 The grass WF refers to the water required for grazed grass and on-farm
346 produced silage. All grass growth was rain-fed implying green water use only. The
347 average beef grass GWF was 7 406 L/kg CW, (range 4 174 L/kg CW to 10 875 L/kg
348 CW). The grass GWF accounted for 88% (range, 84-98%) of the total volumetric WF
349 per kg CW beef.

350 The average sheep grass GWF was 6 699 L/kg CW, (range 4 762 L/kg CW to
351 8 932 L/kg CW). The grass GWF accounted for 87% (range, 73-95%) of the total
352 volumetric WF per kg CW sheep.

353

354 *Stress-weighted water footprint*

355 The average beef stress-weighted WF was 91 L H₂O-eq/kg CW, (range 22 to
356 207 L H₂O-eq/kg CW), implying that each kg of beef produced contributes to fresh
357 water scarcity, equivalent to the consumption of 91 L of fresh water by an average
358 world citizen. The beef on-farm BWF equates to 2% of the beef stress-weighted WF
359 with the remainder attributed to concentrate water use. 91% of the stress-weighted
360 impact for beef concentrate production was due to the irrigation of rape-seed meal
361 produced in the US which had a large blue water irrigation demand (Table 1).

362 The average sheep stress-weighted WF was 2 L H₂O-eq/kg CW (range 1.3 L
363 H₂O-eq /kg CW to 3.5 L H₂O-eq /kg CW), implying that each kg of sheep meat
364 produced contributes to fresh water scarcity, equivalent to the consumption of 2 L of
365 fresh water by an average world citizen. The sheep on-farm BWF equates to 67% of
366 the sheep stress-weighted WF.

367

368 *Water use through intensification*

369 Table 4 presents the national herd sizes, average farm area for specialised
370 beef and sheep farms in Ireland along with the water consumed for grass growth and
371 the volume of water available through precipitation. The baseline value for the beef
372 and sheep sector (2007-2009) referenced in Food Harvest 2020 (DAFM, 2010), and
373 the 2015 sector value is also indicated. The water required for grass growth was
374 30% and 27% of available fresh water production in 2010 and increased to 36% and
375 38% in 2015 on specialised beef and sheep farms, respectively.

376

377 **Discussion**

378 *International water footprint comparison*

379 In this study the total volumetric WF for the beef study farms was 8 391 L/kg
380 CW and 7 672 L/kg CW for the sheep study farms. The largest contributor to the WF
381 for both systems was GW for grass growth, 87% and 91% on the beef and sheep
382 farms, respectively, reflecting the importance of rain-fed grass as a source of feed on
383 livestock production systems. High utilisation of grass as a source of feed is one of
384 the driving forces behind the competitiveness of rainfed grass-based production
385 systems which require low inputs of concentrates or other forages. The WF of
386 concentrates for the beef and sheep meat production systems in this study was 921

387 L and 936 L/kg CW with concentrates making up 11% of total DM intake on beef
388 farms and 8% of DM intake on sheep farms in this study. Furthermore, only a small
389 proportion of the components required for the production of concentrate for the beef
390 and sheep study farms required irrigation.

391 The WF results available in the literature for the production of beef and sheep
392 production vary considerably due to the use of different calculation methods, system
393 boundaries, functional units (carcass weight and live weight) and assumptions
394 pertaining to feed consumption and composition. As >90% of Irish beef and 72% of
395 sheep meat is exported to international markets, it is important to compare the WF of
396 Irish livestock systems to cognate studies from other regions. A study by Mekonnen
397 and Hoekstra (2010) comparing the WF of animals and animal products reported an
398 volumetric WF of Irish beef as 5 684 L/kg CW (96% GW) and a volumetric WF of
399 Irish sheep meat as 3 199 L/kg CW (90% GW). The results presented by the WFN
400 (Mekonnen and Hoekstra, 2010) used data on livestock numbers, feed requirements
401 and system management information from international datasets, rather than data
402 specific to farm scale production systems. Use of national scale data can lead to an
403 over or underestimation of the demands for freshwater at farm level.

404 A study of the volumetric WF of beef and lamb meat in the UK (Chatterton,
405 2010) quantified a UK national volumetric WF of beef as 14 967 L/kg CW (99% GW)
406 and a volumetric WF of lowland lamb of 21 831 L/kg CW (99% GW). The WF results
407 of the UK study (Chatterton, 2010), calculated using a LCA model, considered the
408 feed requirements based on daily live weight gain, utilising farm specific data for
409 pasture production, feed composition and consumption. While the production
410 systems studied by Chatterton (2010) would not be dissimilar to Irish systems, the
411 WF results reported in this study were much lower. The results presented in this

412 study can be considered a more realistic evaluation of the WF for beef and sheep
413 produced in Ireland as fewer assumptions were required due to the nature of data
414 collected from the study farms. This was especially the case for green water required
415 for grazed grass and forage production as well as the metering of on-farm blue water
416 use.

417 There are a number of international studies which consider blue water use
418 only in their estimation of a WF of livestock production systems. The total volumetric
419 BWF of pasture based beef farms in this study was 169 L/kg CW which ranged from
420 19 – 173 L/kg CW. The WF of beef cattle in Australia was computed for six
421 theoretical, geographically defined production systems. The results varied from 25 to
422 234 L/kg live weight (LW), where water use referred to the consumption of
423 freshwater from ground and surface water resources only (Ridoutt *et al.*, 2012a). A
424 study by Wiedemann *et al.* (2016b) calculated the total consumptive blue water use
425 of Australian grass-finished beef production systems in eastern Australia as ranging
426 from 118 to 332 L/kg LW.

427 The total volumetric BWF of sheep in this study was 37 L/kg CW, which
428 ranged from 22 to 64 L/kg CW. Wiedemann *et al.* (2016a) calculated the total
429 consumptive blue water use of Australian lamb from the major production regions of
430 New South Wales, Victoria and South Australia, reporting a BWF range of 58 L/kg
431 LW to 239 L/kg LW (average LW per lamb was 51kg). Ridoutt *et al.* (2012b)
432 reported a volumetric blue WF of Australian lamb, produced in Victoria, of 1 831 L
433 per head of lamb (average LW per lamb = 53kg) with 92% of BW occurring on-farm
434 for livestock drinking water.

435 The lower WF results presented in the present study were mainly influenced
436 by differences in methodology, climate and differences in farm management. In

437 Australian livestock systems it is often necessary to create dams and water
438 reservoirs for animal drinking supply which can have large evaporative losses. These
439 losses accounted for 40% of the total BW consumption in the study by Ridoutt *et al.*
440 (2012a). Furthermore, there was a large irrigation component to the BWF of the
441 Australian production systems which is not encountered on pasture based systems
442 in Ireland.

443

444 *Impact of water consumption*

445 The greatest contribution (98%) to water stress from Irish beef production
446 systems was through the use of irrigated crops for beef concentrate production. The
447 use of rapeseed meal grown and irrigated in the U.S.A which has a moderate degree
448 of water stress (0.499), accounted for 87% of the share of water stress in the
449 production of concentrates with maize gluten from the U.S.A and molasses from
450 Pakistan (stress index of 0.967) accounting for the remaining impact. The beef on-
451 farm BWF in this study was 2.3 L H₂O eq/ kg CW. The average volume of water
452 required on-farm for animal drinking water and cleaning was 1 256 664 L/year;
453 coupled with a low WSI for Ireland of 0.022 (Pfister *et al.*, 2009) beef production in
454 Ireland had a low blue water use impact associated with on-farm water use.

455 The stress-weighted WF result for the beef farms in this study was in the
456 range of previous estimates and averaged 91 L H₂O eq/ kg CW. The stress-weighted
457 WF for Australian beef produced in 6 distinct geographically defined production
458 systems varied from 3.3 to 221 L H₂O-eq/kg LW (Ridoutt *et al.*, 2012a). The main
459 influence on water stress in the Australian production systems was irrigation of
460 pasture and evaporation from dams used to hold drinking water, depending on the
461 geographic location of the beef system. Another Australian study by Wiedemann *et*

462 al. (2016b) reported a stress weighted WF of beef, produced in eastern Australia,
463 ranging from 8.4 to 104.2 L H₂O-eq/kg LW. The stress-weighted water use was
464 influenced by regional water stress in Australia which averaged at 0.22 (range 0.02-
465 0.85) for irrigation, drinking water and evaporation losses from farm dams. A study in
466 New Zealand of several beef farm classes had a stress weighted WF of 0.37 L H₂O-
467 eq/kg LW (Zonderland-Thomassen *et al.*, 2014). The main uses of blue water and
468 related blue water use impact were associated with pasture irrigation and the rearing
469 of bull calves from dairy systems which have large WF associated with the feeding of
470 milk powder to these animals as calves. The higher result for the Australian beef
471 systems is mainly attributed to a higher degree of water scarcity in Australia (0.402)
472 than in New Zealand,(0.021) (Pfister *et al.*, 2009).

473 The stress-weighted WF result for sheep was 2 L H₂O-eq/kg CW. The main
474 contributor to water stress as a result of the production of sheep was on-farm blue
475 water use (65%) for animal drinking and farm maintenance. The average volume of
476 water used over the six sheep farms was 511 644 L/year. Combined with a low WSI
477 for Ireland of 0.022 the overall impact on fresh water resources as a result of sheep
478 meat production was low. For the production of sheep concentrates, 99% of the
479 related water stress was due to the irrigation of sugar cane for the production of
480 molasses from Cuba which has a national WSI of 0.228 (Pfister *et al.*, 2009). Our
481 stress-weighted WF results for sheep were comparable to similar studies carried out
482 in Australia and New Zealand systems investigating the water use related stress
483 from the production of sheep meat. Zonderland-Thomassen *et al.* (2014) assessed
484 sheep production on several different systems, resulting in an average stress
485 weighted WF of 0.10 L H₂O eq/kg L, of which blue water evapotranspiration on
486 irrigated pasture contributed the most (85% blue water), despite the small areas of

487 land being irrigated (1% of total land area). A study by Wiedemann *et al.* (2016a) of
488 Australian lamb meat indicated a stress weighted WF range of 2.9 to 137.8 L H₂O
489 eq/kg. The results were influenced by regional water stress indexes, 0.37 (range
490 0.01-0.82) in lamb production regions.

491 The specific location of production is a critically important factor when
492 comparing the water use and water stress impact of different production systems
493 internationally, due to regional variation across countries and regions (Pfister *et al.*,
494 2009). The importance of assessing a WF in a specific region is evident from the
495 range of results which have been discussed in the previous sections. Ridoutt *et al.*
496 (2012b) warned against generalisations made about the relationship between meat
497 production, water use and issues with water scarcity, as not all species specific
498 livestock production systems are alike. The differences in production systems along
499 with differences in water footprinting methods render informative and useful
500 comparisons of water resource use difficult.

501 Ridoutt *et al.* (2012b) commented on how some livestock production systems
502 (low input, non-irrigated grazing systems) might be considered a sustainable use of
503 the world's water resources due to its modest impact. Improving grass yields and
504 sourcing feed ingredients from non-water stressed areas will be an important aspect
505 of sustainable livestock production and sustainable water use in the future, since
506 improved efficiency of green water use implies a reduced need for blue water
507 resources for irrigation (Rockström *et al.*, 2010). The results of this study converge
508 with findings of recent research underlining the need to add value to green water
509 (rainfall) rather than blue water (irrigation water) to solve the issue of food security in
510 the 21st century (Rockström *et al.*, 2010). Given that the overwhelming majority of
511 livestock products are exported from Ireland to meet the increasing global demand

512 for animal source food, beef and sheep meat produced on pasture based systems
513 could be considered a sustainable use of water resources. Further to this, production
514 system information should be communicated to consumers to allow a scientific
515 basis for dietary choices (Grunert *et al.*, 2014).

516

517 *Effect of intensification on water demand*

518 The water required for grass growth was seen to increase by 6% and 11% to
519 meet the increased beef and sheep productivity required to achieve Food Harvest
520 targets. Murphy *et al.* (2017) demonstrated how 38% of freshwater available on dairy
521 farms was consumed for grass growth, which is similar to the green water use for
522 grass growth in this analysis. One of the main drivers of intensification in Ireland is to
523 meet increases in feed demand through increased growth and utilisation of grass as
524 a source of feed (O'Donovan *et al.*, 2011b). Grass yields increased by 2.2 t DM/ha
525 from 2010 to 2015 on specialised beef farms and by 2.5 t DM/ha on specialised
526 sheep farms. This aligns with current literature which highlights the importance of
527 increased grass intake on pasture based systems in Ireland as there is scope to
528 improve yields, reduce feeding costs and improve livestock productivity (O'Donovan
529 *et al.*, 2011b, O'Brien *et al.*, 2016).

530 While intensification of agricultural systems can lead to both an increase in
531 productivity and environmental performances (Casey and Holden, 2006a), our
532 analysis has highlighted an increase in fresh water demand on livestock systems in
533 Ireland. While there is scope to increase water utilisation through improved grass
534 yields, continued intensification has been seen to negatively impact water quality
535 which in turn can also negatively affect the growth potential of land (Basset-Mens *et*
536 *al.*, 2009). On the other hand, increasing the share of green water use for animal

537 feed could be seen as a valuable trade off in improving the productivity of pasture
538 based livestock systems and sustainable water use as the demand for blue water is
539 lessened.

540

541 **Conclusions**

542 This study presented the first WF assessment of Irish beef and sheep
543 production systems using farm specific data, which was lacking from the literature.
544 This is an important first step in assessing the demands of fresh water as a result of
545 livestock production in Ireland. This study found that green water for grass growth
546 contributed 88% and 87% to the total volumetric WF of Irish beef and sheep farms,
547 respectively. While the associated impact of blue water use in both production
548 systems was low, a future challenge will be to source concentrate ingredients from
549 areas of low water stress or cultivated predominantly from green water resources.
550 This study also evaluated the sustainability of recent intensification initiatives in
551 Ireland and found that the increases in productivity were aided through an increase
552 in green water use to increase grass yields and utilisation. Hence, converting the
553 water used to grow grass (i.e. green water) into a human food source (i.e. livestock
554 products) with low impact blue water inputs could be considered a sustainable use of
555 water resources. The evaluation of water use for the production of livestock alone
556 cannot infer complete environmental performance but is useful to the discussion of
557 environmental sustainability of pasture based livestock production systems.

558

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666 **Table 1;** *Relative share of concentrate ingredients by dry matter (including country of*
667 *origin), economic allocation and percentage share of green and blue water*
668 *requirements for each crop in the concentrate feed mix for beef and sheep study*
669 *farms.*

Feed ingredients	Ingredient Share, %	Economic			
		allocation factor, %	Origin	Green %	Blue %
Beef Concentrate					
Barley	0.28	92	Ireland	100	
Soya bean hull	0.14	66	Brazil	100	
Wheat Feed	0.12	95	Ireland	100	
Distillers	0.12		Ireland	100	
Palm Kernel	0.1	17	South-East Asia	100	
Rape seed meal	0.1	26	USA	65	35
Maize Gluten	0.08	6	USA	74	26
Molasses	0.06	5	India/Pakistan	44	56
Sheep Concentrate					
Molasses	0.03	5	Cuba	86	14
Soybean meal	0.23	66	South America	100	
Beet pulp	0.1	4	Germany	99	1
Barley grain	0.33	92	Ireland	100	
Wheat grain	0.31	95	Ireland	100	

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671 **Table 2;** Production parameters for 10 beef and six sheep study farms for two years, 2014 and 2015.

Parameter	Beef				Sheep			
	Average	Min ^c	Max ^d	SD ^e	Average	Min	Max	SD
Livestock Unit	117	64	201	50	86	38	216	62
Area, Ha ^a	50	28	89	20	42	18	108	32
Total kg CW output	24 058	6 151	69 979	17 085	14 550	5 414	33 686	9 644
Grazed grass intake, kgDM	272 462	49 470	565 095	136 940	214 768	77 558	545 106	155 665
Grass silage intake, kgDM	159 842	94 466	282 436	64 976	66 636	22 283	172 124	51 119
Total forage intake, kg DM	432 304	143 936	814 014	197 554	281 405	105 536	717 230	205 108
Concentrate intake, kg DM	54 010	4 650	128 100	42 248	6 779	5 130	8 652	1 213
Grass Yield, kg DM/ Ha	8 644	4 683	11 701	1 833	24 592	8 000	42 280	10 389
On-Farm water, Litre/year ^b	1 256 664	367 331	3 728 966	923 667	511 644	169 085	1 021 000	330 903

672

673 ^a Ha = Hectares.

674 ^b Metered farm supply.

675 ^c Min = Minimum.

676 ^d Max = Maximum.

677 ^e SD = Standard deviation.

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679

680 **Table 3;** Calculated blue water footprint (BWF), green water footprint (GWF) and stress weighted WF of 10 beef and six sheep
 681 study farms in litres of water/kg CW output for two years, 2014 and 2015.

Parameter	Beef				Sheep			
	Average	Min ^b	Max ^c	SD ^d	Average	Min	Max	SD
On-Farm BWF	64	19	173	48	37	22	64	11
Concentrates GWF	816	183	1 843	426	936	127	1 765	515
Concentrates BWF	105	23	236	55	0	0	0	0
Grass GWF	7 406	4 174	10 875	2 068	6 699	4 762	8 932	1 398
Total BWF	169	73	409	88	37	22	65	11
Total GWF	8 222	4 871	11 058	1 895	7 635	4 983	9 891	1 467
Total Volumetric WF	8 391	4 993	11 130	1 860	7 672	5 017	9 933	1 471
Stress Weighted ^a On-Farm BWF	2.3	0.7	6.3	1.8	1.3	0.8	2.4	0.4
Stress Weighted Concentrate BWF	89	20	201	46	0.7	0.1	1.3	0.4
Total Stress Weighted BWF	91	22	207	47	2.0	1.3	3.5	0.7

682
 683 ^a Stress-weighted = Stress-weighted WF, weighted using the water stress index.

684 ^b Min = Minimum.

685 ^c Max = Maximum.

686
 687 ^d SD = Standard deviation.

688

689

690 **Table 4;** Production parameters for beef farms in 2010 and 2015 for Food Harvest 2020 targets for specialised beef and sheep

691 farms and volume of water consumed for grass growth.

	Herd Size (x10 ⁶)	Farm #	Farm Size (Ha)	Rainfall ^a (mm)	Total Area (x10 ⁶ Ha)	Grass Yield (tDM/Ha)	Total Grass (x10 ⁶ tDM)	Water available for grass (x10 ¹⁰ m ³)	Grass Water Requirements (x10 ¹⁰ m ³)	Water Consumed (%)	Value €Billions
							Beef				
2010	3.38	77 738	28	1186	2.15	6.7	14.4	2.55	.76	30	1.63 ^b
2015	3.32	78 874	35	1186	2.18	8.9	19.4	3.27	1.18	36	2.27
							Sheep				
2010	2.51	13 555	31	1186	4.17	6.3	2.63	4.95	1.36	27	171 ^b
2015	2.40	15 056	34	1186	4.46	8.8	3.92	6.07	2.30	38	205

692 ^a 30 year long-term average.

693 ^b Baseline value of beef industry from 2007-2009 (DAFM, 2010).

