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Journal
Journal of Animal Science, 100(11)

ISSN
0021-8812

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Publication Date
2022-11-01

DOI
10.1093/jas/skac297

Peer reviewed

Journal of Animal Science, 2022, **100**, 1–13
https://doi.org/10.1093/jas/skac297
Advance access publication 5 September 2022
Environmental Animal Science

How advances in animal efficiency and management have affected beef cattle's water intensity in the United States: 1991 compared to 2019

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Abstract

Updating the static model by Beckett and Oltjen (1993), we determined that from 1991 to 2019, U.S. beef cattle blue water consumption per kg of beef decreased by 37.6%. Total water use for the U.S. cattle herd decreased by 29%. As with the 1993 model, blue water use included direct water intake by animals, water applied for irrigation of crops that were consumed by beef cattle, water applied to irrigated pasture, and water used to process animals at marketing. Numbers of cattle, crop production, and irrigation data were used from USDA census and survey data. On 1 January 2019, a total of 31.7-million beef cows and 5.8-million replacement heifers were in U.S. breeding herds, and 26-million animals were fed annually. In total, the U.S. beef cattle herd (feedlot and cull cows) produced 7.7-billion kg of boneless beef, an increase of 10% since 1991. Beef cattle directly consumed 599-billion L of water per year. Feedlot cattle were fed various grain and roughage sources corresponding to the regions in which they were fed. Feeds produced in a state were preferentially used by cattle in that state with that state's efficiency; any additional feedstuffs required used water at the national efficiency. Irrigation of crop feedstuffs for feedlot cattle required 5,920-billion L of water. Irrigated pasture for beef cattle production required an additional 4,121-billion L of water. Carcass processing required 91-billion L of water. The model estimated that in the U.S. 2,275 L of blue water was needed to produce 1 kg of boneless meat. As with the previous model, the current model was most sensitive to changes in the dressing percentage and the percentage of boneless yield in carcasses of feedlot cattle (62.8 and 65, respectively). In conclusion, with more beef, fewer cows, and lower rates of irrigation, beef cattle's water intensity has decreased at an annual rate of 1.34% over a 28-yr period.

Lay Summary

In 1993, Beckett and Oltjen published an innovative model that evaluated beef cattle's blue water (ground water and surface water) use in the United States. The model stated that to produce one lb. of boneless beef, 440 gallons of blue water were required. Although this model shifted the prevailing acumen regarding beef cattle's water use and became the fifth most cited Journal of Animal Science article in popular press, with today's vast changes in cattle genetics, animal management, and irrigation practices, the value generated in this model has become obsolete. By updating Beckett and Oltjen (1993) with today's agricultural inputs, the present model was the first to use an "apples to apples" strategy to compare beef cattle's blue water use over time. Utilizing USDA irrigation and cattle inventory datasets along with expertise from university extension, the current model determined that over a 28-yr period beef cattle's water intensity per one lb. of boneless beef was 275 gallons, a decrease of 38%. In addition, total water use for the U.S. beef production system decreased by 29%. The principal reasons for these decreases were due to the decrease in water used to irrigate crops and pasture, increased meat per carcass, and improved efficiencies in cattle management and nutrition. Despite these decreases in water use and intensity, water will continue to be a concern for beef cattle production, particularly in the west where surface and ground water are rapidly depleting. The beef industry has made great strides in water reduction but will need to continue to decrease blue water use, for if there is no water, beef cannot be produced.

Key words: Beckett and Oltjen, beef sustainability, irrigation, livestock efficiency, water use

Abbreviations: DDG, dried distiller's grains; DP, dressing percentage; HCW, hot carcass weight; LCA, life cycle assessment

Introduction

In the United States (U.S.), the Western region is enduring a severe drought unseen since 800 C.E. (Williams et al., 2022), triggering blue water (aquifers and surface water) shortages and a cascade of regulations from diverting water from agriculture (Parks and Moriarty, 2021) to restricting household water use (Becker, 2022). Alarms over water utilization have renewed public concerns over agriculture's water footprint. With beef requiring 80% to 260% more water than other meat sources (Mekonnen and Hoekstra, 2010), the expostulation for the consumption of beef by both public and scientific sectors continues to increase. However, over the last 30 yr, agricultural industries have made significant advances in crop yields, crop irrigation practices, and cattle efficiencies (Capper, 2011; USDA-ERS, 2022). Despite these advances, there is a scientific and consumer disconnect between industry advances and beef cattle's water use. Without this understanding, it becomes increasingly difficult to accurately assess how beef production is contributing to water scarcity and how and where the beef industry needs to improve.

Received August 2, 2022 Accepted September 2, 2022.

Although several beef cattle water models exist, their scope is limited to comparing current production practices rather than comparing temporal changes. In 2011, utilizing life cycle inventories for six different beef production systems in the United States, a farm to gate life cycle assessment (LCA) determined beefs' water intensity to range from 3.3 to 221 L water per kg live weight (Ridoutt et al., 2012). In 2019, using the process based Integrated Farm Systems Model, Rotz et al. determined U.S. beef cattle water intensity to be 2,034 L/kg hot carcass weight (HCW). The issues with comparing models and determining changes in water use over time was illustrated in Menendez and Tedeschi (2020), where the researchers stated that broad water values used in literature, inconsistent units, and vast regional differences prevent the direct comparison between models. Therefore, in order to compare beef cattle's water use over time an "apples to apples" methodology is needed.

Of all the beef cattle water models, Beckett and Oltjen (1993) has continued to be the most cited water assessment for beef and was the fifth most cited article in the Journal of Animal Science in popular press (Altmetrics, 2022). However, changes in beef cattle management and crop production practices now make Beckett and Oltjen's water estimate of 3,682 L/kg of beef obsolete. Due to the model's static design and the use of USDA agricultural datasets, this was an appropriate model for updating beef's water use. As such, the present study sought to incorporate the most recent USDA and university extension values on crop yield, crop irrigation, animal performance, and feedlot ration data into the original Beckett and Oltjen model in order to make direct comparisons of beef cattle's water use and intensity from 1991 to 2019.

Materials and Methods

The present study was based on the static model designed by Beckett and Oltjen (1993) depicting beef cattle production in the United States constructed in Excel. All production schemes within the model were represented on an individual U.S. state basis (Table 1). The water accounted for in the model was limited to blue water (surface and groundwater). Natural participation (green water) that fell on crops or pasture was not included in this model. Recycled water (purple water) and wastewater (gray water) was also excluded within the model. Figure 1 shows the schematic of the main components used within the model. As in the original Beckett and Oltjen model, individual states were grouped into regions for presentation purposes (Table 1). To make direct comparisons to Beckett and Oltjen, regions were identical to that of the 1993 model. These regions were originally assembled with expertise from feedlot nutritionists and extension specialist to represent homogenous feeder groupings.

Table 1. Regions used in analysis

Region	States included
1	WA, OR, ID
2	MT, ND, SD
3	WY, CO, UT
4	NM, TX. OK
5	KS, NE
6	MO, IA, MN, WI, IL, MI, IN, OH, NY, PA
7	CA, AZ, NV
8	AL, AK, AR, CT, DE, FL, GA, HI, KY, LA, ME, MD, MA, MI, NH, NJ, NC, RI, SC, TN, VT, VA, WV

Cattle inventory

Beef cow inventory was provided by the National Agricultural Statistics Service (NASS) for the year 2019 (USDA, 2019; Table 2). The number of calves was estimated assuming 86 calves weaned per 100 cows per year. Although this may be an underestimate of percentage of calves with Cow Herd Appraisal Performance Software (CHAPS) data goals of 91% weaned calves, the authors wanted the model to account for all types of cow-calf production systems including those that had unreported lower calving rates and those calves born but not weaned. The replacement rate of heifers and cows per bull ratio was based on regional survey data (Asem-Hiablie et al., 2015, 2016, 2017, 2018). Heifer replacement rate averaged 20% to 28% and the number of cows per bull ranged from 18 to 20. Average weights for cows, bulls, and replacement heifers were based on USDA-NASS datasets (2019). Weaned calf weights were based on CHAPS (2018) and university extension expertise. Regional differences in weights were accounted for using Asem-Hieablie survey data (Asem-Hiablie et al., 2015, 2016, 2017, 2018). To properly assess regional cattle weights, regional weights provided by the survey data were then weighted to the USDA 2019 national averages. Average weights were 590, 290, 355, and 704 kg for cows, weaned calves, replacement heifers, and bulls, respectively.

Beef cattle lifecycle

To determine the number of cull cows utilized in the beef supply, cull cow numbers were calculated by multiplying by number of replacement heifers and average weight of the cows. This number was then multiplied by 95% to assume death loss of 5%. Death loss was overestimated to account for cull cows that did not make it to harvest. Although cow-numbers fluctuate from year to year, the model assumed the national cow herd stays relatively constant from year to year, so the number of replacements was equal to the number of cows being culled from the cow herd each year. Average dressing percentages (DP) for cull cows was 50% of live weight and average beef from carcass was valued at 65% of HCW (Harris et al., 2018).

Animal water intake

Although several models have been developed since the original Beckett and Oltjen (1993) water assessment, Winchester and Morris (1956) remains one of the most reliable water models to predict beef cattle water intake on large scales (Spencer et al., 2017; Ward et al, 2017; Zanetti et al., 2019). As such the Winchester and Morris (1956) model was used in the present model to predict total water intake by class of cattle (Table 2). These data were fit into regression equations SAS 5.1 (SAS Institute, Cary NC) according to the following model: water intake = b_0 + b_1 weight + b_2.temperature + b_3.temperature^2 (coefficients can be viewed in Beckett and Oltjen, 1993). Average annual temperature for all 50 states were based on the National Oceanic and Atmospheric Administration data base (NOAA, 2019; Table 2).

The yearly predicted total water intake for cows was calculated as the sum 1) of all cows with calves (86% of all

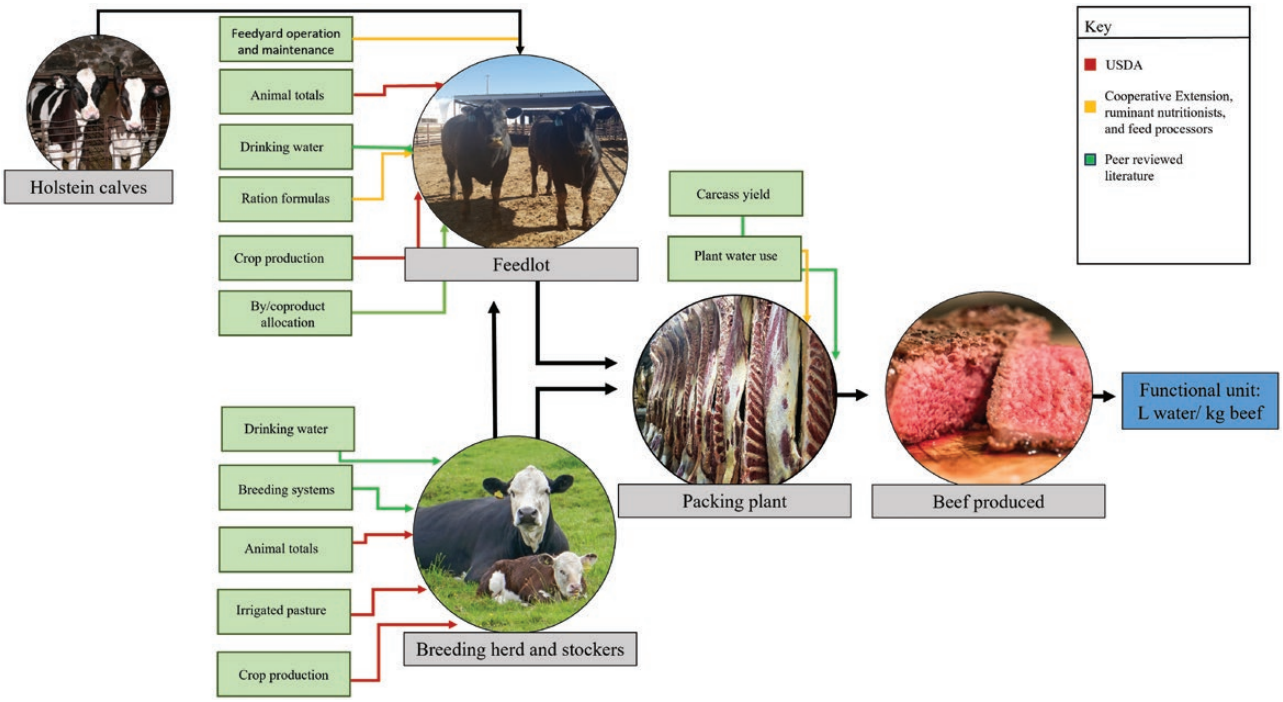

Figure 1. Schematic of the water inventory used for U.S. beef production.

Table 2. Breeding herd and stocker numbers

Region[2]	Average annual temp, °C	Inventory (1 January 2019[1])				Water source	
		Beef cows	Calves	Heifers	Bulls	Drinking, 10^6 L	Nonpasture irrigated feed, 10^6 L
1	8.4	1,271,000	1,093,060	285,000	81,042	3,011	21,303
2	6.7	4,241,000	3,647,260	725,000	253,243	10,081	67,500
3	8.2	1,846,000	1,587,560	368,000	112,521	4,308	30,442
4	16.2	7,285,000	6,265,100	1,270,000	467,236	16,833	154,051
5	11.7	3,470,000	2,984,200	455,000	205,744	8,098	60,250
6	9.9	5,003,000	4,302,580	881,000	331,701	12,072	87,322
7	14.7	1,087,000	934,820	234,350	66,068	2,534	21,452
8	13.9	7,487,700	6,439,422	1,649,796	438,496	17,121	157,411

[1]Cattle inventory data based on USDA-NASS datasets.
[2]See Table 1 for states in regions.

cows) times the water consumption for lactating cows for 4 mo of the year, 2) of all cows without calves times the water consumption for maintenance animals for 4 mo of the year, 3) of all pregnant cows (92%) times the water consumption for pregnant cows for 8 mo of the year, and 4) of all nonpregnant cows (8%) times the water consumption for maintenance cows for 8 mo of the year (Beckett and Oltjen, 1993). Yearly water intake for calves was calculated for 205 d (~7 mo). After time of weaning, replacement heifers consume water as predicted by the water intake equation for that class of cattle. The rest of the calves either entered the feedlot directly (18%; USDA-NASS, 2019) or were stocked for a period of time. Stocker cattle consumed water according to the prediction equation for growing calves. Calves entering the feedlot consumed water as feeders. Bulls consumed water as predicted by the total water consumption equations for their respective classes. Equations predicting water intake represented both water drunk directly by the animal and water contained in the feed. To determine direct water consumption, water in the feed was subtracted from the total water intake predictions. In accordance with ruminant nutritionists, no changes were made to the DMI for all classes of breeding and stocker cattle with 2% of BW, DMI of calves was estimated to be 2.5% of BW (Beckett and Oltjen, 1993). An average of 75% DM of the breeding herd feedstuffs was used to calculate the amount of water contained in the feed that the animals consumed. This feedstuff-bound water was subtracted from the total water intake predictions to give an estimate of the water consumed by drinking (Beckett and Oltjen, 1993). Although it was suggested by Beckett and Oltjen that 75% possibly overestimates the DM content in the feed, this was the best value available. As with the 1993 model, water consumed by feedlot animals was based on NRC calculations and estimated to be 45 L per animal per day (NRC, 2016).

Animal feed water numbers

The USDA-NASS provided the number of hectares of each crop, irrigated hectares for each crop, and the yield of each crop by state (Tables 3–6; USDA-NASS, 2018). Although, data was collected for individual states, in order to make direct comparisons between the current model and the Becket and Oltjen model, data was once again represented on a regional basis. Total water applied was the product of the number of irrigated hectares and the applied water per hectare. As in the 1993 model, irrigation was also calculated for the production of sorghum and barley; however, because these crops resulted in less than 1% of the feed water use, these feedstuffs were not shown in individual tables. Unlike the 1993 model, soy production was incorporated into this model, but like sorghum and barley because soy represented less than 2% of the feed water use, soy water use was not presented in a table format. At the time of the Beckett and Oltjen's model publication distiller's grains (DDGs) were not readily used. Unlike cotton seed hulls or bakery waste, DDGs are considered a coproduct and not a byproduct (Rausch andBelyea, 2006; Olsen and Capehart, 2019). Therefore, to accurately account for the water use of DDG's and to be in accordance with ISO 14040 standards (ISO, 2006) and LEAP guidelines (Boulay et al., 2021), a mass allocation of 50% was used (Bernardi et al., 2012). Blue water production for ethanol was based on Liu et al. (2019) and blue water use for corn production was based on USDA datasets (2018) resulting in a water intensity of 35 L/kg of DDG produced. Water production values for corn gluten were limited, but Rotz et al. (2019) utilized an unpublished value 3 L/kg. Therefore, for the current analysis the water value of 3 L/kg of corn gluten was used. To account for the water used to extract minerals and vitamins for cattle rations, the number was based on LCA Gabi data as reported in Klopatek et al. (2022; 44.6 L/kg of mineral/vitamin). Most fat sources fed to cattle are considered byproducts (Zinn and Jorquera, 2007), therefore the current model utilized inedible tallow as the major fat source and treated this tallow as a coproduct. The largest source for tallow is the beef cattle industry. To avoid double counting water, the blue water for tallow production was only accounted for postharvest. Utilizing World Bank data and industry consulting, water used for the rending of inedible tallow was assumed to be 1 L/kg of product (World Bank, 2007).

In 1993, pasture irrigation values were not yet reported and thus the value used was that estimated for irrigated

Table 3. U.S. corn production[1]

Region	Total area, ha	Percentage of area irrigated	Applied water, 10^6 L/ ha	Total water, 10^6 L	Total yield, 10^6 kg	Liter of water/ kg of corn
1	150,452	72	7.7	1,124,323	2,025	555.2
2	3,180,022	29	1.9	234,007	31,286	7.5
3	554,419	89	4.5	1,291,165	4,718	273.7
4	836,943	61	4.6	1,596,818	5,948	268.4
5	5,778,916	35	2.4	5,691,760	61,675	92.3
6	19,961,136	7.0	1.5	1,172,001	236,711	5.0
7	634,43	96	9.1	551,108	754	730.6
8	2,555,146	17	2.4	1492,847	25,489	58.6
Sum	33,080,481	–	–	13,154,028	368,606	–
Weighted average	–	14	2.8	–	–	35.7

[1]Values based on USDA-NASS 2018 datasets.

Table 4. U.S. alfalfa production[1]

Region	Total area, ha	Percentage of area irrigated	Applied water, 10^6 L/ ha	Total water, 10^6 L	Total yield, 10^6 kg	Liter of water/ kg of alfalfa
1	791,808	80	6.0	3,813,029	7,802	489
2	1,969,814	17	3.9	1,306,763	7,783	168
3	804,642	83	5.5	3,712,973	6,441	577
4	240,640	44	6.5	680,146	2,154	316
5	633,820	29	3.2	597,756	5,419	110
6	2,044,866	1.0	1.7	28,078	14,286	2
7	564,480	97	12.4	6,750,842	8,318	812
8	194,427	23	2.7	120,290	1,425	84
Sum	7,244,497	–	–	17,009,878	53,627	–
Weighted Average	–	35	6.63	–	–	317

[1]Values based on USDA-NASS 2018 datasets.

Table 5. U.S. corn silage production[1]

Region	Total area, ha	Percentage of area irrigated	Applied water, 10^6 L/ ha	Total water, 10^6 L	Total yield, 10^6 kg	Liter of water/ kg of corn silage
1	157,423	72	6.1	776,911	10,081	77.1
2	229,457	29	3.4	55,258	8,373	6.6
3	115,371	89	5.6	515,998	5,804	88.9
4	155,804	61	3.7	381,988	6,015	63.5
5	246,858	35	2.9	218,578	8,968	24.4
6	1,179,660	7.0	4.6	122,237	51,555	2.4
7	238,362	96	9.8	2,102,535	14,770	142.4
8	258,681	17	4.2	107,668	11,114	9.7
Sum	2,581,616	–	–	4,281,174	116,680	–
Weighted average	–	29	4.2	–	–	36.7

[1]Values based on USDA NASS 2018 datasets.

Table 6. U.S. wheat production[1]

Region	Total area, ha	Percentage of area irrigated	Applied water, 10^6 L/ ha	Total water, 10^6 L	Total yield, 10^6 kg	Liter of water/ kg of wheat
1	1,647,477	20	5.2	1,728,402	8,417	205.4
2	5,838,810	1.0	2.3	177,554	17,057	10.4
3	118,951	44	3.6	183,828	327	562.7
4	1,762,408	9.0	3.5	566,121	3,472	163.1
5	3,362,941	4.0	2.1	273,541	8,896	30.8
6	1,732,461	2.0	1.7	57,340	7,594	7.6
7	123,145	100	8.1	993,059	736	1350.4
8	713,815	3.0	2.1	49,262	2,954	16.7
Sum	15,300,006	–	–	4,029,107	49,452	–
Weighted average	–	6.0	4.2	–	–	81.0

[1]Values based on USDA-NASS 2018 datasets.

Table 7. U.S. irrigated pasture[1]

Region	Total area, ha	Applied water, 10^6 L/ha	Percentage of irrigated pasture used for beef	Water used for beef production, 10^6 L
1	378,119	5.5	88	1,827,237
2	209,233	3.4	75	530,623
3	451,987	4.2	83	1,538,008
4	159,053	2.9	90	413,422
5	33,542	2.5	94	78,242
6	9,510	3.4	94	30,233
7	349,989	7.8	72	1,958,294
8	30,491	3.2	80	69,535
Total	1,621,923	–	–	6,445,594
Weighted Average	–	5.0	81	–

[1]Values based on USDA NASS 2018 datasets.

alfalfa in California. At the time the authors acknowledged that although utilizing alfalfa irrigation values for pasture may have inflated the beef's water use, this was the best irrigation value available at the time. Unlike the 1993 model, the current model was able to utilize pasture hectares and pasture irrigation data as reported by USDA-NASS. Beef specialists were consulted to estimate the percentage of irrigated pasture hectares devoted to beef production (breeding and stocker cattle) within each state. Water devoted to beef production through irrigated pasture was calculated by multiplying the total water applied to irrigated pasture and the percentage of irrigated pasture used in beef production within each state (Table 7).

Feedlot animals

The total gain, days on feed, and daily gain of all animals on feed were based on survey datasets (Asem-Hiablie et al., 2015, 2016, 2017, 2018) and university extension expertise, principally researchers in the NCCC308 group (Nutrition and Management of Feedlot Cattle to Optimize Performance, Carcass Value and Environmental Compatibility Group). Weight of harvested animals was based on USDA-NASS (2019) values and regional differences in harvest weight were based on survey datasets (Asem-Hiablie et al., 2015, 2016, 2017, 2018). On average, cattle were assumed to gain 245 kg, over a 159-d period with an average daily gain of 1.68 kg/d. In Arizona and California, based on university extension estimates, it was assumed that 40% of the feeder cattle population were Holstein steers resulting in a higher days on feed in these areas averaging 265 d. Death loss was assumed to be 2% (Klopatek et al., 2022). Based on state beef extension specialists' estimates, feedlot rations and feed to gain conversions were formulated by state. Rations by region (weighted by number of cattle in each region) are shown in Table 8. Dry matter content of the various ration components (NRC, 2016) were used to calculate the water content of the diets. Crops grown in each state were preferentially fed in feedlots in that state, implying that water required to grow feedstuffs was used at a regional water efficiency. If a state did not produce enough of crop to provide the state's feedlots with the required amount of feed, the additional crop needed was fed at the national average water efficiency. Although other models take into account the transpatial nature of cattle movement into different regions (Menendez and Tedeschi, 2020), the current model did not take into account the transpatial movements in order to ensure an apples to apples comparison between models. To comprehensively incorporate feedlot water usage, additional water for dust control was incorporated (31-L feedlot animal; Rotz et al., 2019). Water used for steam flaking corn was based on 0.6 L/kg of corn (Wiedemann et al., 2016). Total water required to maintain the feedyard, and grow the irrigated feedstuffs fed to feedlot cattle is included in Table 9. After the feed required for feedlots was removed from the respective state's production supply, the remaining feed became available to the breeding herd and stocker cattle within that state.

Feed for stockers, cows, and holsteins

Additional feed for stockers and cows were estimated based on Beckett and Oltjen (1993) and updated via livestock extension experts. As with the feeder cattle, if there was not adequate feed supplied in the state, the additional commodity was assigned the national average water use efficiency. Amounts of feed fed to the breeding herd and stocker cattle are shown in Tables 10 and 11.

For Holstein calves, water required for the growth was accounted for from the time they left the dairy (approximately 3 d of age) until the time they entered the feedlot (90 d). Nutrients supplied to the dairy calves included corn, alfalfa, mineral and milk replacer. A typical calf growing ration was used to calculate the feed requirements for the

Table 8. Feedlot rations by region[1]

Region[2]	Feed to gain	Alfalfa, %	Corn, %	Wheat, %	Corn silage, %	Sorghum, %	Barley, %	Soy, %	Distiller's grains, %	Mineral vitamin mix, %	Fat, %	Corn gluten, %	Byproduct[3], %	Dry Matter, %
1	6.5	5	19	3	10	0	5	0	15	4	2	0%	38	56
2	6.5	2	55	2	10	0	0	4	14	4	1	5%	6	71
3	6.5	3	61	3	7	3	0	0	12	4	2	1%	5	62
4	6.7	5	58	6	4	0	0	0	12	4	2	8%	3	88
5	6.5	4	54	5	9	0	0	0	14	4	2	2%	7	87
6	6.9	3	46	2	18	0	0	7	10	4	2	3%	6	69
7	6.4	5	62	6	0	2	0	0	15	4	2	0%	6	88
8	6.9	4	34	5	30	0	0	1	5	4	2	4%	11	73

[1]Rations were weighted by number of feeder cattle per region.
[2]See Table 1 for states in regions.
[3]Product output from a unit process that is not a determining product (ISO 14040 definition).

Table 9. Water utilized in the feedlot

Region	Total animals fed/ yr[1]	Water for dust control and steam flaking	Water consumed by drinking, 10^6 L	Water for irrigated feed, 10^6 L
1	1,117,893	2,499	8,175	327,615
2	952,481	4,591	6,006	47,697
3	2,068,556	10,552	10,609	1,162,519
4	5,616,729	25,362	38,012	1,794,293
5	9,415,747	42,793	60,997	1,380,596
6	5,238,645	23,707	41,392	115,222
7	1,519,607	9,262	16,179	1,078,042
8	187,043	501	1,336	14,083
Total	26,116,700	119,267	182,706	5,920,066

[1]Based on 1 January 2019 USDA-NASS datasets.

Table 10. Feedstuffs fed to cows and bulls[1] (kg/yr)

Region	Alfalfa	Corn	Wheat/grass hay	Corn silage
1	272	0	14	0
2	499	50	45	227
3	499	0	45	23
4	181	14	0	0
5	263	91	23	408
6	227	45	91	907
7	499	23	91	0
8	227	23	23	227

[1]Does not include irrigated pasture.

Table 11. Feedstuffs fed to stockers[1](kg/yr)

Region	Alfalfa	Corn	Wheat/grass hay	Corn silage
1	227	0	23	0
2	136	91	0	681
3	272	0	68	0
4	23	0	113	14
5	0	91	91	544
6	0	91	0	907
7	227	0	45	0
8	23	0	227	68

[1]Does not include irrigated pasture.

calves (NRC, 2016). Water required for the feedstuffs was calculated at the national average for each crop due to the small amount of feed that is fed to this class of animal and the difficulty in determining the geographical location of growing Holstein calves. Direct water consumption of Holstein steer calves resulted in 11 L/d.

Packing house water numbers

The water required to process beef carcasses was based on 10 estimates provided by large packers across the country. The estimated water required to process the animal included the time the animal reached the abattoir throughout fabrication processing. Estimates were provided on a liter of water per head basis. The location of packing houses included California, Nebraska, Utah, Oklahoma, Arizona, Texas, and Kansas. The average water utilized per head was 2,850 L resulting in a total water use of 91.2-billion L to process all cattle.

Statistics

The Sensitivity Analysis Model was used to assess the sensitivity of key parameters (i.e., m^3 blue water per ton of feed commodities) consistent throughout livestock water footprint publications (Hoekstra and Mekonnen, 2012; Menendez and Tedeschi, 2020). We increased and then decreased the parameter by 10% and noted the overall change in water intensity for beef production. The value of 10% was selected to enable direct comparisons between the current model and the 1993 Beckett and Oltjen model.

Results and Discussion

In the present study, the model predicted that 2,275 L of blue water was needed to produce 1 kg of boneless beef in the U.S. beef cattle production system for 2019. The total beef herd required 17,784,402 10^6 L in the current model as compared to 25,305,550 10^6 L of blue water in Beckett and Oltjen (1993), a decrease in water use of 29%. Compared to Beckett and Oltjen (1993), beef cattle's water intensity (L/kg of boneless beef) decreased by 37.6% since 1991, or 1.35% per year. The decrease in water use and intensity for beef was attributed to changes in irrigation practices, crop yields, the incorporation of by products and coproducts, and changes in animal efficiencies.

Distribution of water

Although total water use and water intensity were considerably different between 1991 and 2019, the distribution of water use was relatively similar (Figure 2). In both models, irrigation water for feed in the feedlot, irrigated pasture for breeding herd and stockers, and irrigated feed for the breeding herd and stockers were responsible for the largest portions of water use. This is consistent with other models that have shown irrigation of feed to be the number one source of beef cattle's water footprint (Capper, 2012; Asem-Hiablie et al., 2019; Rotz et al., 2019; Klopatek et al., 2022). There were differences between the proportion of both the irrigated pasture and irrigated feed for the breeding herd and

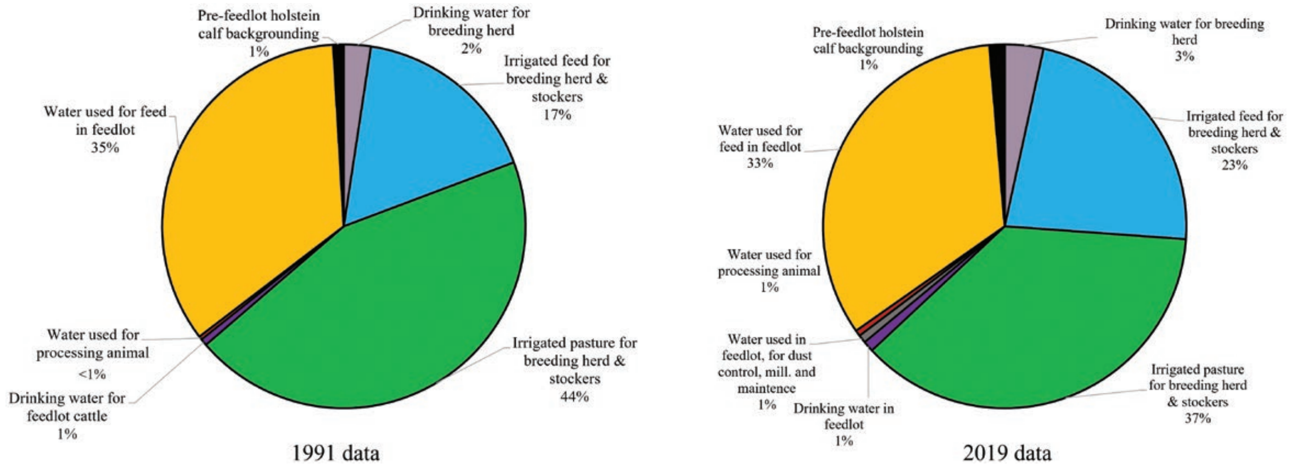

Figure 2. U.S. beef productions blue water use distribution from Beckett and Oltjen's 1991 data compared to 2019 data.

Table 12. Difference in U.S. cropland, applied water, and yield between 1991 and 2019

Crop	Total area	Proportion of area irrigated	Applied water per ha	Total water, L	Total yield	Water per kg of product
Corn	+39%	+3.0%	−32%	0.0%	+116%	−54%
Corn silage	+10%	+130%	−15%	+115%	+60%	+34%
Wheat	−29%	−14%	−6.0%	−34%	−4.0%	−32%
Alfalfa	−24%	+52%	−9.0%	+4.0%	−16%	+23%

stockers between the models with an 8%-unit decrease in irrigated pasture and 6%-unit decrease in irrigated feed from 1991 to 2019. Unlike the 1991 dataset, the current model incorporated water for dust control, maintenance, and running feed mills (flaking of corn). However, maintenance/dust control was only 1% of total water use. Water distribution for processing animals, drinking water, and Holstein calves was consistent between the models.

Changes in pasture and crop production

From 1890 to 2019, irrigation of crops in the United States increased from 3-million acres to over 58-million acres (USDA-ERS, 2022). This rapid expansion in irrigation allowed for significant gains in cropland productivity aiding in the enhancement and mechanization of livestock feeding operations. While the total irrigated land area has steadily increased, the average amount of water applied per hectare (water intensity) has steadily decreased (USDA-ERS, 2022). The diminishing water intensity has been attributed to changes in on-farm irrigation conveyance and application technologies, as well as regional shifts in irrigated areas and evolving crop patterns (USDA-ERS, 2022). Although recent estimates have determined that the crops used to feed livestock require approximately 23% of total U.S. blue water consumption (Richter et al., 2020), the results of the current study demonstrate that while cattle continue to require a high blue water utilization (as compared to other food sources), irrigation water use for beef has decreased significantly over the last 30 yr.

While the sum of water used to irrigate all U.S. corn remained unchanged from 1991 to 2019 (1.32 10^{13} L), the water applied per ha decreased by 32% (Table 12) and crop yield increased by 116%. The decrease in water applied has been attributed to changes in technologies and water applications using soil moisture sensors, weather tracking, irrigation scheduling tools, flow meters, and plant condition monitoring technology (USDA-ERS, 2022). In addition, the widespread adoption of precision-farming technologies and crop breeding improvements has supported the increase in yield. Specifically, Rizzo et al. (2022), determined that the increased yield in corn was attributed to a decadal climate trend (48%), agronomic improvements (39%), and improvement in genetic yield potential (13%). It is important to note that the continued decrease in corn water intensity for beef production has a trickledown effect that results in a lower water intensity for accompanying coproducts such as distillers-grains.

Similar to corn production, the water applied per ha of alfalfa and corn silage also decreased (Table 12). However, the amount of irrigated land for alfalfa and corn silage increased (up 52% and 129%, respectively) resulting in greater total water use. Despite the increased total water use, only a minimum effect was observed on beef's water intensity. The minimum effect was due to the relatively low incorporation of these ingredients into feedlot rations (Table 8).

One of the largest changes between the 1993 model and the current model was the irrigation intensity, or applied water, of irrigated pasture. Today, the USDA conducts an agricultural census that publishes applied water numbers for irrigated pasture. As a result, the average applied water decreased from 7.5 to 4.9 10^6/ha between 1991 and 2019, decreasing the irrigated pasture water use for beef by 74% (Table 13). For reference, if the 2019 dataset used the 7.5 L 10^6/ha value, the current water intensity for beef would be 16% higher. Furthermore, in both the 1991 model and the current model irrigated pasture water use was the 4th greatest factor effecting beef cattle's water intensity (Table 13). This demonstrates

Table 13. Difference in irrigated pasture between 1991 and 2019

Item	Percent difference between 1991 and 2019			
	Total area, ha	Applied water per ha	Proportion of irrigated pasture used for beef	Total water used for beef production
Irrigated pasture	–15%	–53%	0%	–74%

Table 14. Change in U.S. beef cattle production from 1991 to 2019

Item	Beef production in 2019		Beef production in 1991		Percent Change	
	Feedlot cattle	Cull cows	Feedlot cattle	Cull cows	Feedlot cattle	Cull cows
No. of animals	26,116,700	5,574,739	28,397,470	5,747,100	–8.03	–3.00
Average body wt, kg	626	592	500	476	+25.1	+24.3
Dressing percentage, %	62.8	50.0	62.0	55.0	+1.29	–9.09
Carcass beef, kg/animal	393	296	310	262	+26.8	+11.0
Boneless yield in carcass, %	65.0	65.0	66.7	66.7	–2.55	–2.55
Boneless beef, kg per animal	255	192	207	175	+23.4	+9.91
Total beef production, 10^6 kg	6,670	1,072	5,873	1,004	+13.6	+6.79

the importance of utilizing the most accurate and up to date irrigation numbers.

Changes in diets, management, and animal performance

Over the past 30 yr. feedlot rations have undergone substantial changes. In Beckett and Oltjen (1993), neither byproducts (e.g., bakery waste, potato waste) nor coproducts (e.g., DDGs, corn-gluten, tallow) were utilized in their analysis. The lack of incorporation was principally because neither coproducts nor byproducts were readily fed in the early 1990s. Although the first study feeding distillers grains to cattle was published in 1907 (Schabinger and Knodt, 1948), distillers' grains did not become a major feed source until the late 1990s and early 2000s when the ethanol industry began to boom (Wallander et al., 2011). In the current model, depending on region, byproducts and coproducts accounted for 20% to 52% of feedyard rations. The highest inclusion of byproduct feeding was in Region 1 where potato byproducts were fed at a rate of 40%. The most utilized coproduct was DDG, with rations averaging 12% nationally, followed by corn gluten at 3%. With many byproducts and coproducts having lower total water use and lower water intensities compared to forages and concentrates, their inclusion reduced the beef systems water use. In addition, advances in cattle genetics and ruminant nutrition have resulted in a systematic shift to incorporate a higher percentage of concentrates and a lower percentage of forages in feeder cattle rations. These changes to the proportion of concentrate to forages in rations favors a lower water use profile. For example, both the amount of alfalfa and wheat fed in feeder cattle rations decreased nationally (1.5% and 5.7%, respectively). However, while the rate of corn in rations increased from 49% to 54%. Corn was produced at a lower water intensity relative to irrigated forages, resulting in a lower blue water intensity for beef. For irrigated feedstuffs fed to the breeding herd and stockers, minimum differences between 1991 and 2019 were observed. Despite the cow herd decreasing by 6% (Table 14) the average cow size increased by 113 to 159 kg, increasing the amount of feed per head. Therefore, only a small decrease in beef cattle feed water use (7%; not including irrigated pasture) was observed in the breeding herd/stocker sector.

The sensitivity analysis showed that a 10% change in animal performance (dressing percentage, boneless yield, or feed to gain) had some of the greatest effects on beefs water intensity (Table 15). Similar to improvements in crop yield, genetic and managerial improvements have also increased the efficiency and production of beef cattle. In Beckett and Oltjen (1993), animal DP were assumed to be 62% for feeder cattle and 55% for cows (Table 14). According to the 2016 National Beef Quality Audit and university extension expertise, these numbers were adjusted to 63% for feeder cattle and 50% for cows. The increase in DP for feeder cattle was attributed to changes in genetics and management strategies (Harris et al., 2018; Personal Communication-university extension). Utilizing a 50% DP for cull cows was considered a more reasonable estimate according to extension experts and more consistent with that observed during beef quality audits. Feedlot cattle DP had the largest influence on beef's water intensity with a 10% change having an 8% effect on water intensity (Table 15). In comparison, a 10% change in cull cow DP would only affect beef cattle's water intensity by 1%. In contrast to DP, yield per carcass decreased from 67% to 65%. This change could possibly be due to changes in yield grades and the increased amount of fat produced per animal. As with DP, a 10% change in carcass yield resulted in an 8% change to beef's water intensity. Regarding feed to gain, based on the sensitivity analysis a 10% change in feed to gain altered water intensity by 3% (Table 15). Although the Beef Cattle Research Council (2022) in Canada has reported that feed to gain has improved by over 30% the last 30 yr, the current model used only a marginal improvement in feed to gain of 6.7:1 to 6.4:1 (Personal communication ruminant nutritionists, and university extension).

One of the greatest differences in cattle performance from 1991 to 2019 were the increases in cattle weights and the amount of beef produced from the cattle herd (Table 14). With genetic emphasis (EPDs) on growth and efficiency, cow and feeder cattle weights have increased over the last 30 yr (USDA-ERS,

Table 15. Model sensitivity to parameter changes 1991 compared to 2019

Standard	Parameter initial value (2019)	Percentage Change, %	Parameter initial value (1991)	Percent change, %	Difference in parameter values: 2019 compared to 1991, %
Dressing percentage for feedlot cattle, %	62.8	7.93	62.0	8.60	+1.27
Percentage boneless yield in carcass (feedlot animals), %	65.0	7.93	66.7	8.60	–2.62
Animals harvested (On Feed)	2.62E+07	7.93	2.84E+07	5.24	–8.53
Total water applied to irrigated pasture, L/ha	4.90	3.61	7.50	4.44	–53.1
Area of irrigated pasture, hectares total (not just for beef)	1,621,923	3.61	1,869,018	4.44	–15.2
Total gain for animals on feed (average), kg	265	3.61	197	2.74	+26.7
Feed to gain	6.40	2.78	6.69	2.74	–1.52
Days on feed, d	159	2.41	150	2.72	+5.73
Area of irrigated corn, ha	4.75E+06	2.44	3.23E+06	2.55	+32.0
Total water used for irrigated corn, L	1.31E+13	2.44	1.32E+13	2.55	–0.38
Percentage corn grain in feedlot rations	0.57	1.51	0.49	2.40	+14.0
Corn yield, kg	3.69E+11	1.39	1.71E+11	1.86	53.7
Alfalfa yield, kg	5.36E+10	2.00	6.37E+10	1.83	18.9
Area of irrigated alfalfa, ha	2.57E+06	2.09	2.23E+06	1.73	13.0
Total water used for irrigated alfalfa, L	1.70E+13	2.11	1.64E+13	1.73	+3.59
No. of replacement heifers	5,868,146	2.11	5,747,100	1.65	+2.06
Average cow weight, kg	592	1.31	476	1.52	+19.6
Dressing percentage of culled cows, %	0.50	1.46	0.55	1.46	–10.0
Percentage boneless yield in carcass (cull cows), %	0.65	1.46	0.67	1.46	–2.62
No. of beef cows	3.17E+07	1.37	3.38E+07	1.46	–6.76
Water intake by breeding herd and stockers, L	5.99E+11	0.33	6.06E+11	0.24	–1.05
Dry matter in feed for breeding herd, %	0.75	0.15	0.75	0.09	0.00
Holstein calf growth, L	2.36E+11	0.13	2.37E+11	0.09	–0.32
Cow to bull ratio	19:1	0.11	20:1	0.09	–5.26
Water consumed in the feedlot, L	3.37E+11	0.10	3.70E+11	0.11	–8.99
Percentage calves weaned, %	0.86	0.85	0.85	0.04	+1.16
Water used for processing animals, L	9.13E+10	0.05	7.85E+10	0.03	+14.0
Dry matter intake for cows, bulls, and replacement heifers, % BW	2.00	0.03	0.02	2.00	0.00
Average calf wt., kg	290	0.05	136	0.20	+53.2
Average replacement heifer wt., kg	404	0.05	272	0.10	+32.7
Average bull wt., kg	705	0.02	680	0.10	+3.48
Water for DDGs, L	1.10E+11	0.16	NA	NA	NA
Water for wheat, L	4.03E+12	0.65	6.11E+12	0.40	–51.6

2021). This increase in cattle weight has resulted in a 28% increase in beef produced per animal (Table 14). Therefore, despite the decrease in cowherd size (and fewer feeder cattle harvested) there was an increase in total beef production. Although the larger steer size resulted in greater amounts of drinking water consumed in the feedlot (10%), only a minimum effect was observed on water intensity. Interestingly, leaving all model parameters equal to 2019 values, and if the 1991 beef production values were used in the 2019 model, water intensity would have increased by 14%. This demonstrates how efficiency of the beef cattle system has resulted in significant reductions in the beef cattle water intensity.

Comparing water models

In 2010, Mekonnen and Hoekstra calculated that the global total water (green, gray, and blue) intensity for beef was over 128,594 L/kg with a blue water intensity for beef averaging 5,129 L/kg. Although these values provided insight into global beef water intensities and were highlighted on the Water Footprint Network (2011), these values were not representative of U.S. beef production (Rotz et al., 2019; Menendez and Tedeschi, 2020). The U.S. beef production system has implemented a multitude of technological advancements in genetics, animal nutrition, and management resulting in lower environmental footprints as compared to global beef averages (Capper, 2011). This was demonstrated by Capper in 2011 when Capper determined how advancements of the U.S. beef systems resulted in a significantly lower water intensity of 1,763 L/kg HCW. In addition, the Capper study showed that from 1977 to 2007, beef cattle's water intensity had decreased by 12%. In Capper's model, processing was excluded, and the functional unit was based on HCW rather than boneless beef. Adjusting the functional unit to boneless beef (assuming 65% of HCW was boneless beef) and assuming 1% of the total water used was from processing (Beckett and Oltjen, 1993) Capper's 2007 study would have equated to 2,739. This value would then be 19% higher than the present study's water estimate and 25% lower than Beckett and Oltjen (1993). Considering values used in the study ranged from 2000 to 2007, Capper's value was comparable to the current model, assuming the downward trend of a 1.35% per year in beef's water intensity. Similar to Capper's work and the current study, a decrease in water intensity was also observed for Canadian beef systems (Legesse et al., 2018). Specifically, from 1981 to 2011, the estimated intensity of blue water per kilogram of boneless beef decreased by 20%. However, compared to the United States, the Canadian beef system required far less irrigation resulting in a blue water use of only 459 L/kg of boneless beef.

In 2019, Rotz et al. determined that the water intensity for beef was 2,034 L/kg HCW. Adjusting the functional unit to boneless beef (65%), the water footprint would equate to 3,129 L/kg of boneless beef. This value was 26% higher than the current model's assessment. The differences between the Rotz model and the current model's water intensities were most likely due to model design and deviations between the water values used for feedstuffs in feeder cattle rations. Rotz model was based on a 30-yr simulation and the current model was static in design based principally on USDA datasets. The greatest difference between the models was the water allocation for coproducts. In the Rotz model, the fat added to the diets required 50 L/kg. In the present model, because the majority of fat utilized in the feedlot rations was considered to be a coproduct of beef production (inedible tallow and grease; Zinn and Jorquera, 2007) and to avoid double counting water in the beef system a significantly smaller number of 1 L/kg was used. To assess the water use of DDGs, a coproduct mass allocation was used (as recommended by LEAP guidelines; Boulay et al, 2021). The allocation was based on USDA production data where DDGs required 50% of the water footprint used, though this value is likely to range by region (Menendez and Tedeschi, 2020). This allocation was nearly identical to those used in Haque et al. (2022) who used an allocation of 49%. In comparison, Rotz et al. (2019) used an economic method and determined that the water utilization of DDG was 180 L/kg based on 21.5% allocation. This water value was approximately five times higher than the current value of 35 L/kg of DDG in the current model. The difference between these values were most likely due to the water numbers used for corn processing for DDGs. Unlike the Rotz model where DDG water was determined by the Integrated Farm System Model simulation, the current model utilized a USDA national average of 35.7 L and the water for the processing was based on Liu et al. (2019). It is not known what specific values were used for irrigated pasture for the ISFM model.

Conclusion

From 1991 to 2019, U.S. beef cattle's blue water intensity decreased by 37.6% from 3,682 L/kg of beef to 2,275 L/kg of beef with total water use for the entire beef cattle herd decreasing by 29%. The decrease in blue water was principally due to decreased irrigation water intensity on pasture and crops, the shift to incorporating byproducts and coproducts into feedlot rations, and the changes in cattle size and beef produced per animal. Despite the decrease in water intensity and water use, water will continue to be a concern for beef cattle production, particularly in the west where surface and ground water are rapidly depleting. With the water scarcity issues in the western U.S. cattle production may be forced to move to areas with greater blue and green water availability. In future work to account for the movement of cattle, water models will need to further account for trans-spatial movement of cattle. In conclusion, although the industry has heavily focused on greenhouse gas mitigation there needs to be continuous attention on water use and water mitigation.

Acknowledgment

This research was made possible by the Beef Checkoff.

Conflict of Interest Statement

The authors declare no real or perceived conflicts of interest.

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