Measuring and Mitigating GHGs: Beef

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There are millions of farms globally, each using a unique set of practices to cultivate their products in the local climate and soils. Thus, for any commodity, there are many thousands of different production systems and many thousands of different sources of greenhouse gases. The relative GHG emissions of producing the same product may differ drastically depending on how and where it is grown. To fully understand how to mitigate emissions and on which farms to focus mitigation efforts, we need a better grasp of the variations and gaps in data.

The authors do not think all the information to quantify GHG emissions from the beef value chain exists. At the very least, not in one place; this document is our attempt to collate currently available information. This is a working draft; debate, discussion, and comments are welcomed to advance the understanding of this topic. WWF will be producing similar pieces on other key food commodities to stimulate similar discussions. All comments should be justified with evidence and data and sent to Emily Moberg at GHGCommodities@wwfus.org.

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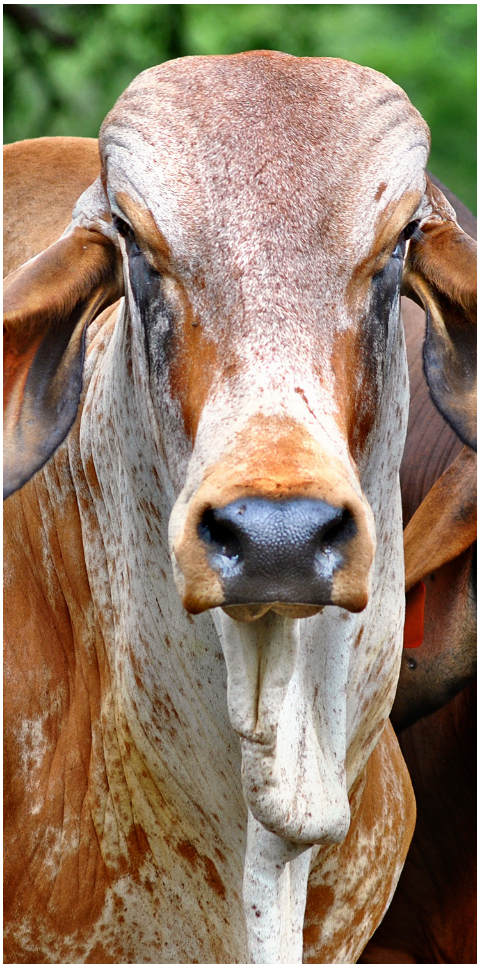


ABOUT BEEF

Beef is one of the most widely consumed meats in the world, accounting for about 25% of meat production worldwide, after pork and poultry at 38% and 30%, respectively. In 2019, the global cattle population was about 1.5 billion animals.[1] About 31% was in Asia, 26% in Latin America, 24% in Africa, 7% in North America, 8% in Europe, and 2% in Oceania. 65.9 million tons of beef were produced globally.[2] As of 2005, 56% of beef was produced by the specialized beef sector and 44% by the dairy herd.[3] The U.S. was the largest beef producer in 2020 (20.4%) followed by Brazil (16.7%) and the EU (12.9%). These three regions accounted for approximately 50% of the world's beef production.

Beef is produced from both beef and dairy herds in countries around the world. Cattle also can provide draft power and have cultural significance for many people. As ruminants, they are capable of digesting grasses that non-ruminants like humans cannot metabolize and converting them into proteins that we can eat.

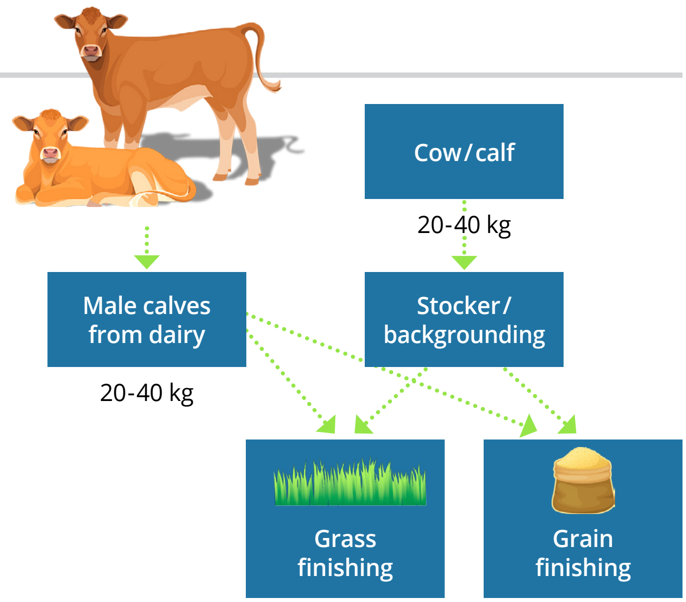
However, this digestive process also produces methane (CH_4), and human overconsumption of red meat can cause negative health outcomes, making beef a controversial dietary component for both environmental and human health.

BEEF SUPPLY CHAINS

Beef production consists of three key phases: cow-calf, stocker/backgrounding, and finishing. Although cattle spend most of their lives on pasture, the type of finishing system impacts the carbon footprint of beef. The time spent in each phase varies dramatically across regions.

Dairy cattle also produce beef, from male calves as well as from culled females and breeding males.

Once cattle have reached slaughter weight, they are transported to slaughterhouses where they are killed, dressed, and processed into meat and other byproducts (including bonemeal and leather). Meat is then packaged and transported to retail.



Beef cattle life cycle for grass-finished and grain-finished in the U.S. adapted from Broocks et al. with animal weights representing global range from GLEAM.

kg at slaughter
Dairy: 138-605
Beef: 93-605

Figure 1: Beef cattle life-cycle

GHG EMISSIONS FROM BEEF SUPPLY CHAINS

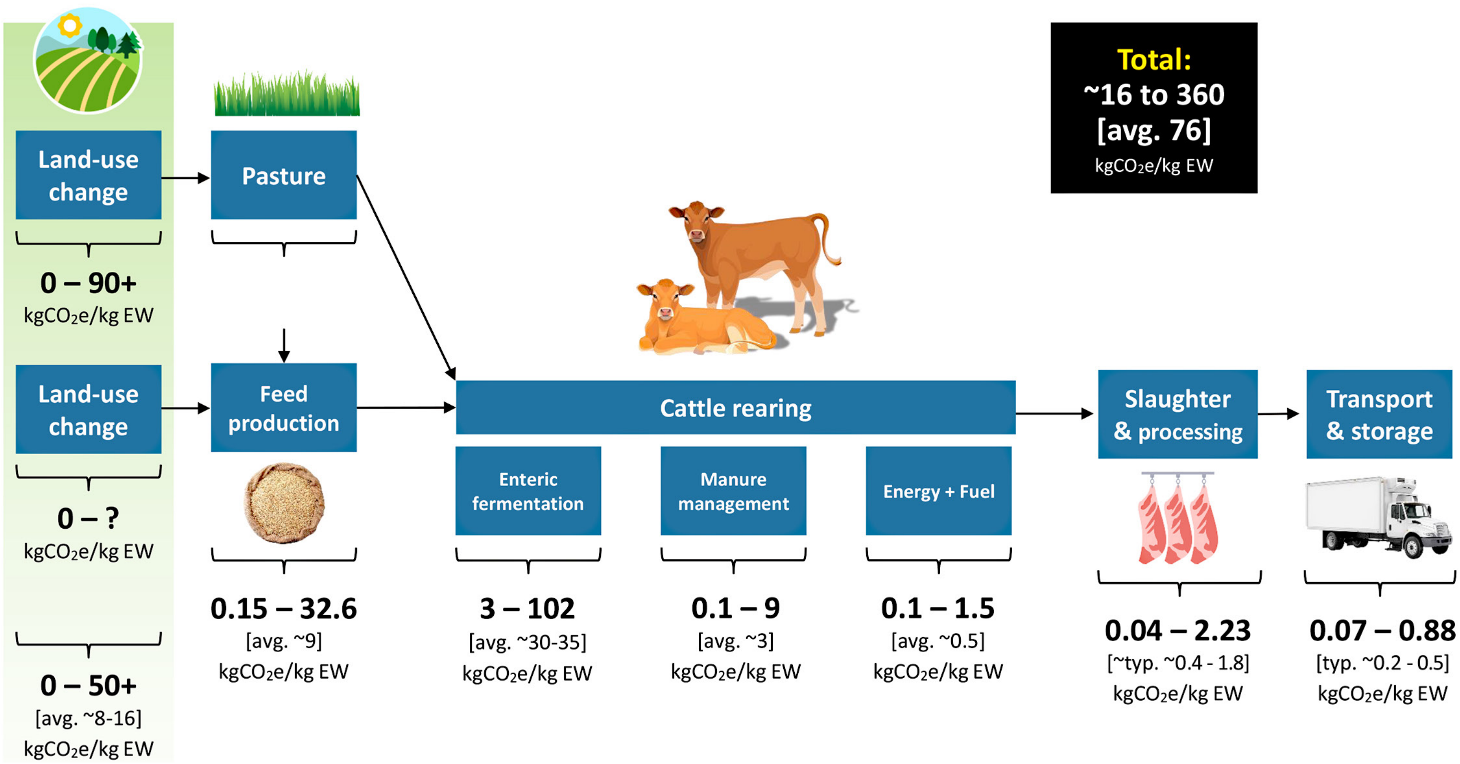
Of meats, beef has the greatest average global emissions intensity per kilogram. Most of these emissions (over 80%) are attributed to production.[4] Net GHG emissions from beef production globally differ significantly, implying that there is substantial opportunity for improvement among a sizeable proportion of producers; often high emissions intensity comes from inefficient production. Most emissions come from biological sources (rather than energy use on farm). Globally, large amounts of land are used for grazing; carbon is stored in the soils of grazing land, which can be either a source or sink of carbon depending on management.

Primary GHG emissions associated with beef include all CO_2, CH_4, and N_2O produced during the production of feed, maintenance of animals, and handling of manure. Across production systems and geographies, estimates of GHG emissions range from about 16 to 360 kg CO_2e/kg edible meat (EW) to retail (avg. ~76 kgCO_2e/kg EW)[5]. Most of these emissions occur from cradle-to-farmgate.

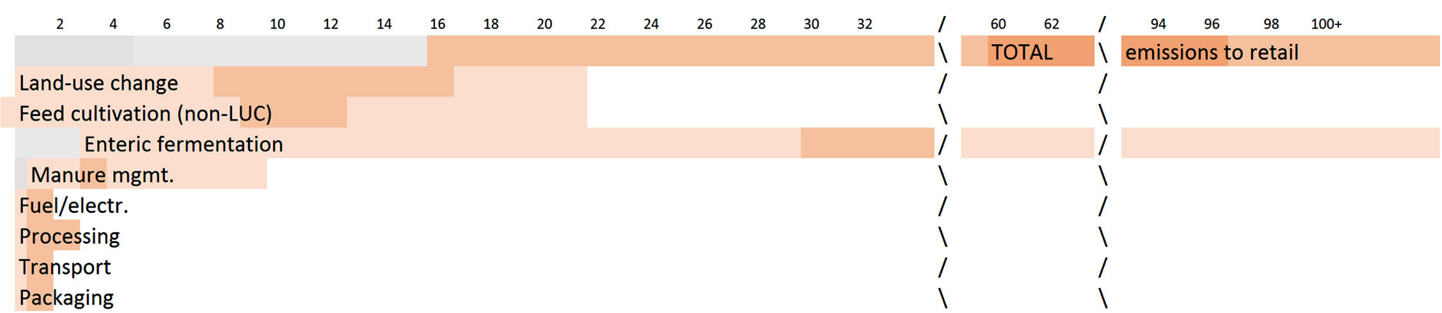
Average emissions intensities to farm-gate for beef produced in grass-based and mixed farming systems were estimated at 95 and 58 kg CO_2e/kg edible weight (EW), respectively; cattle fed primarily through feedlots produce meat at 21 kgCO_2e/kg EW.[6] However, grass-finished beef utilizes forage from human-inedible plants.

This variability arises from variable emissions across

Figure 2: Range of GHG emissions from beef supply chains



each stage of production. The full range of impacts (in kgCO_2 e/kg edible meat) is shown below, with the typical range highlighted in darker orange. Note that the full range has been broken in two places to illustrate the wide magnitude of emissions from beef production.



Feed

The feed eaten by cattle constitutes a large part of beef's overall footprint, and is a major determinant of the amount of enteric fermentation produced.

The inputs (like seeds and fertilizer) used to produce the feed, plus fuel for farm machinery and N_2O emissions from the soil and water all contribute to emissions from feed. In addition, when other habitats are converted to cropland or pasture, the biomass removed contributes to the overall footprint. For cattle, the land-use change (LUC) component for soy and for palm oil is typically considered, although other crops like maize can also have non-negligible conversion footprints.

The feed quality and digestibility essentially determine how quickly the cattle grows; they also determine the amount of enteric methane (see below) produced. Thus, feed quality has its own footprint and also influences the time-to-slaughter and methane produced.

The global GHG emissions associated with feed range from <0 to over 270 $kgCO_2e$/kg EW (including LUC emissions);[7] across 10 roughly continental-scale regions, emissions from feed (averaged across grassfed, feedlot, and mixed systems) range from 8 to 45 $kgCO_2e$/kg EW.[8]

- **Grazing:** Grassland cattle's emissions from feed average about 45 $kgCO_2e$/kg EW; over half of this (25 $kgCO_2e$/kg EW) comes from pasture expansion in Latin America. About a third of beef comes from grassland systems. Emissions are as low as 3.8 $kgCO_2e$/kg EW in Russia and as high as 85 $kgCO_2e$/kg EW in Latin America. Most of the remaining emissions come from N_2O from applied and deposited manure, which ranged from 2 to 44 $kgCO_2e$/kg EW.[9] Note that the quality of pasture has a large effect on the cattle growth and total GHG footprint (e.g., in one case five times the difference across degraded and improved pastures[10]).

- **Non-grazed feed:** For feedlot and mixed systems, GHGs from feed are lower, with an average footprint of 17 kgCO_2e/kg EW for mixed systems and of 7 for feedlot. The range across regions is 5 - 14 kgCO_2ekg EW for feedlot and 8-30 kgCO_2e/kg EW for mixed. Most emissions again come from applied manure for fertilizer (1.2 -10 kgCO_2e/kg EW across regions), but between 0.1 and almost 2 kgCO_2e/kg EW come from LUC of palm and soy.[11]

Note that the lifetime amount of feed consumed varies dramatically based on the time females take to calving and how long it takes cattle to reach slaughter. When cattle reach these milestones faster (there are often more than two times differences across more and less efficient systems), less feed is used.

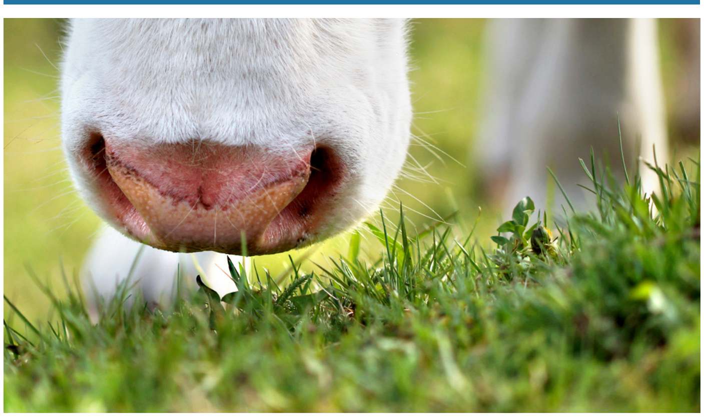
Land-use change (LUC) emissions can take place from direct land-clearing for cattle grazing or from the transformation of forest to cropland to cultivate feed crops. Significant pasture expansion and forest area decrease were observed in Latin America and Africa from 1990-2006.[12] The major global cropland expansions, especially in Brazil and Argentina, were for maize and soybean production. While LUC contributes a significant quantity to total emissions in certain regions, these estimates differ greatly.[13]

- **World Resources Institute (WRI) deforestation estimate:** 1.65 GtCO_2e/yr, or 25 kgCO_2e/kg EW (average of 3 Mha converted to pasture per year globally; assuming carbon content of forest is 150 tC/ha, multiplied by 0.65 to account for WRI's data set ranging from 35% to 100% tree cover)[14]
- **Poore and Nemecek estimate:** 0.89 Gt/yr or 13.4 kgCO_2e/kg EW (calculated assuming 56% beef from dairy herd)
- **GLEAM:** 0.39 Gt/yr (from only select Latin America and Caribbean [LAC] countries[15]) from pasture expansion or 8.3 kgCO_2e/kg EW as of 2010

Sequestration in grazing lands: Well-managed grazing lands can sequester carbon over time; how much and how quickly depends on local conditions including how degraded the soil is currently. Measuring this sequestration is still nascent. In addition, grazing lands that are converted to row crops release carbon, so keeping cattle on natural grasslands can be an important part of habitat (and carbon) maintenance.

Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool. Soil carbon sequestration rates strongly depend on agro-ecological conditions. Meta-analyses conducted by Conant et al. (2017) find that soil carbon sequestration in beef grazing systems has a global mitigation potential of 0.04-0.8 $GtCO_2$/yr.[16] In regional analyses, annual carbon sequestration rates are between 0.2 and 0.5 tC/ha/yr for the European grassland systems[17] and between 0.4 and 0.5 tC/ha/yr for the native prairie in the Northern Great Plains in the US.[18] Because cattle can use between 0.005 and over 0.1 ha per kg of beef, the amount of sequestration per unit product is likely to be highly variable.

Emissions from feed range from negative to well-over 100 $kgCO_2e$/kg EW. Estimates near the low-end are without land-use change and with rotational grazing that allows for sequestration of carbon. LUC footprints are globally averaged over 10 $kgCO_2e$/kg EW but can be much higher regionally.



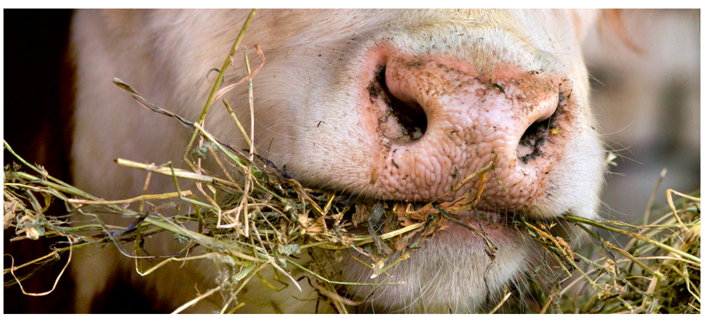
Enteric fermentation

Cattle produce methane as part of their digestion. When digestibility of feed is low, they produce more methane. Thus, both the quality of feed and how long the animal is alive strongly influence the amount of methane produced. Chang et al. (2021) estimated methane emissions intensity of 22-26 $kgCO_2e$/kg EW for beef cattle globally;[19] GLEAM values for 2010 are 35, 43, 37, and 10 $kgCO_2e$/kg EW, respectively, for aggregate, grassland, mixed, and feedlot beef. These values vary widely by geography from a low of 11 in Eastern Europe to a high of 76 in South Asia (with lower and higher values for specific feed-systems).[20] This is broadly consistent with data in Poore and Nemecek's review, which has an average enteric methane footprint ($kgCO_2e$/kg EW) of 42 (18-102 range) for beef herds and 14 (range 2.5-35) for dairy-herd beef.

Enteric methane emissions not only contribute to global warming but also represent an energy loss amounting to up to 11% of dietary energy consumption.[21]

Enteric fermentation can be mitigated with dietary manipulation, feed additives and forage quality; [22] these changes may also dramatically change the time needed to reach slaughter weight.[23]

Emissions from enteric fermentation can range from 3 to over 100 kgCO_2e/kg EW. Estimates near the low-end are from feedlot systems with high-quality feed and short times to slaughter. The higher values tend to be from cattle eating low quality forage over long life-spans.



Manure management

Cattle produce large amounts of manure. Manure handling, storage, processing, and application can produce CH_4 released from organic material and N_2O emissions. Methane and nitrous oxide are produced through different biochemical reactions, so the amount of each gas produced depends on the manure composition and the temperature and oxygenation conditions of storage.

The range of emissions from manure is not as variable as those from feed or enteric fermentation. The global average is a little over 3 kgCO_2e/kg EW (range across geographies and production systems from 1.6 to 9.5),[24] although individual operations with GHG intensive manure management practices may be higher (e.g., Poore and Nemecek report a few studies with footprints over 10 kgCO_2e/kgEW for manure).

The emission quantity is correlated to type of management, environmental conditions, and the manure composition. For example, the methane conversion factors for selected management practices (which essentially multiply the amount of manure):[25]

- 1-2% for pasture depending on temperature
- 2-5% for solid storage
- 3-30% for pit storage less than 1 month
- 10% for burned as fuel

Effective manure management involves controlling how manure decomposes in order to reduce emissions.[26]

Manure management contributed 3 kgCO_2e/kg EW (range: 1.6 – 9.5 kgCO_2e/kg EW); higher emissions are from lagoons or pits, while lower emissions come from pasture spread. Use of anaerobic digesters to capture methane for biogas can produce lower footprints.




Energy use

Direct energy inputs on-farm include electricity, diesel, gasoline, natural gas, propane, and other fuels. Indirect energy implies that consumption takes place off-farm. These indirect energy inputs are typically from production of fertilizer and pesticides. Direct and indirect energy-use emissions are small (0.2 - 1.2 $kgCO_2e/kgEW$; average 0.5).[27]

Post-farm emissions

Post-farm emissions arise from transportation, slaughter and processing as well as packaging. Most of these emissions are from the fossil fuel emissions used in producing electricity or directly burned as fuel.

- **Slaughter/processing:** Emissions from slaughter and processing to carcass are not as well characterized as on farm emissions. Poore and Nemecek estimated processing emissions at 1.8 $kgCO_2e/kg$ EW. Other estimates are much lower, around 0.2 kCO_2e/kg EW.[28]
- **Transport:** Emissions for transportation depend on both the distance traveled and the mode of transit; per kg-kilometer, boats and trains have much lower emissions than trucks which are then lower than those from airplanes. Estimates range from 0.1 - 0.6 $kgCO_2e/kg$ EW.[29]
- **Packaging:** Emissions from packaging depend on the type of packaging and arise largely from energy use in production. These typically add between 0.2 - 0.4 $kgCO_2e/kg$ EW.[30]

Post-farm emissions can vary but are typically below 2-3 $kgCO_2e/kg$ EW, or much less than on farm emissions.

PRODUCTION SYSTEMS

The aforementioned processes often differ systematically across different types of "production systems."

Beef production systems are typically categorized as either beef herd or dairy herd. Within these, production systems may be categorized by feed (grazing rangeland, seeded pasture, feedlot systems or a combination) or by the production stages such as cow-calf, backgrounding, or fattening/finishing. Because beef is produced by different actors, one challenge in assessing GHG emissions from the final product is that many studies focus only on one part of the beef supply chain.[31]

Beef herd:

Meat from beef herds tends to have a higher GHG intensity than meat from dairy herds because some emissions in dairy are allocated to milk and beef herds have a larger proportion of breeding animals. Estimates of GHG intensity from beef herds range from about **79 kgCO_2e/kg EW** (range: 28 – 182)[32] to **101 kgCO_2e/kg EW.**[33] Across regions, this varies widely as well. About 56% of beef globally comes from beef herds.

Dairy herd:

In dairy herds, beef comes from bull calves, non-replacement heifers, and culled cows. GHG emissions are allocated or shared between the milk and meat produced over the animals' life span. Globally, intensity ranges from **7.8 to 75 kgCO_2e/kg EW with an average of about 27.**[34]

Feeding system:

- **Rangeland grazing:** Rangelands are those lands that naturally produce forage plants suitable for grazing but where rainfall is too low for growing crops. Global average GHG emission is about 95 and 58 kg CO_2e/kg EW, for grazed and mixed (grazed + fed), respectively.[35]

- **Seeded pasture:** Seeding pasture improves unproductive pastures and grasslands with the best mix of legumes and seeds for cattle; this should reduce emissions from enteric fermentation but, depending on location, may increase or decrease emissions from the pasture.

- **Feedlot:** A type of feeding operation that is used in intensive animal farming to increase the amount of weight gain on a high-energy, grain-based diet. The average GHG emission is about 21 kgCO_2e/kg EW at farm gate.[36]

Production Stages:

Few studies broke down emissions by stage of production, despite the fact that this information will be critical for targeting mitigation. The analysis below has been conducted for cattle in the US (avg. emissions ~32 kgCO_2e/kg EW).[37] Percentages below are from that study, which is unlikely to be representative worldwide.

- **Cow-calf:** A cow-calf operation is a method of raising beef cattle to produce young calves for later sale. Over 70% of total emissions was associated with this stage, mostly from methane.
- **Backgrounding:** An intermediate operation that begins after weaning and ends on placement in a feedlot. Most common feed is forage combined with grains to increase animal weight. This stage contributed about 12% of emissions.
- **Fattening/finishing:** The finishing phase is the primary difference between grass-fed and grain-fed systems. Grain-fed finishing uses feedlots to complete the final phase. This stage contributed about 17% of total emissions with much of it from upstream (feed) sources.

Across these systems, the amount of feed consumed can vary widely, ranging from about 13 kg feed dry matter (DM) intake/kg EW in an intensive fattening system with dairy bull calves and up to 32 kg feed DM intake/kg EW for beef from a beef breed system.[38]

REGIONAL VARIATION

Emissions also vary regionally. This is a function both of which practices tend to be used in a region (which are not inherently geographic) and local climatic factors. Local climate often influences animal performance as well as feed quality.

The magnitude of the carbon footprint varies significantly from country to country. Average emission intensity globally is 76 kgCO_2e/kg EW for beef. Figure 2 shows that emissions intensities for beef production are highest in sub-Sahara Africa and South Asia. Higher emissions are caused largely by low feed digestibility, poorer animal husbandry and lower slaughter weights, and higher age at slaughter. In Latin America and the Caribbean, one-third of the emissions originate from pasture expansion into forested areas. In Europe, about 80% of the beef is produced from dairy animals such as surplus calves and culled cows, resulting in lower emissions intensities.[39]

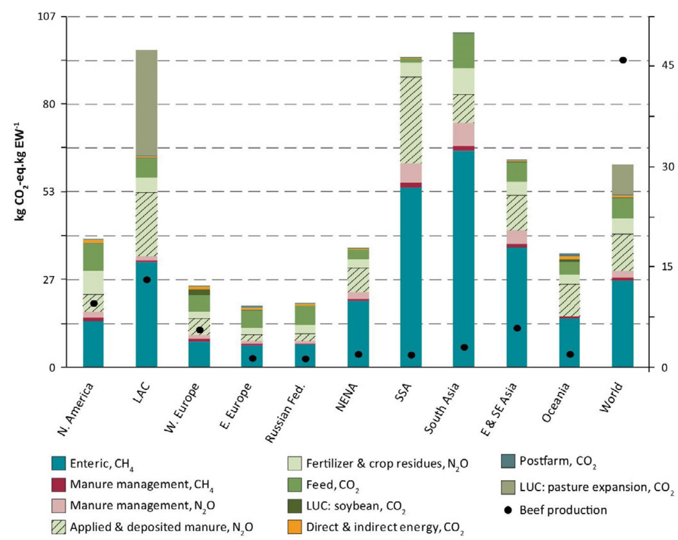


Figure 3. *Regional variation in beef production and GHG emission intensities (Source: GLEAM, adapted from Gerber). LAC (Latin America and the Caribbean), NENA (Near East and North Africa), SSA (sub-Saharan Africa). Units were converted from carcass to edible weight using the 0.75 conversion specified in GLEAM documentation.*

Countries within these regions also differ; the table below illustrates some key properties for select countries.

Table 1.

	Total beef produced (metric ton)[40]	% beef from beef herd[41]	Avg. forest loss for pasture (k ha)[42]	Area of grazing land (million ha)[43]	Intensity of GHG emissions from beef (kgCO_2e/kg EW)
Argentina	3.14 million	69	118	74.7	avg. LAC: 91[44]
Brazil	10.2 million	69	1,457	173	67-350 (avg.151)[45]; (avg. LAC: 91)[46]
China	5.94 million	77	13	393	(avg E & SE Asia: 73)
India	0.9 million	40	4	10.3	(avg E & SE Asia: 73)
USA	12.4 million	76	41	245	36 - 79
Zambia	0.19 million	41	34	20	(avg SSA: 90)

OUTLIER EMISSIONS SOURCES

The variability in emissions per kg of edible beef highlights the large mitigation potential that exists across current practices. Here we highlight the “low hanging fruit”, or practices that drive unusually high emissions intensity. These practices may be good targets for initial screening for improvement.

- **Land-use change in feed or pasture:** emissions from land-use change for cattle is a major global source of emissions, totaling over 1 $GtCO_2e/yr$
- **Optimized diet and feed use:** improvements in animal health to decrease time to slaughter and increase digestibility can both reduce the amount of feed eaten and reduce the time over which enteric fermentation occurs
- **Manure management:** when manure is stored in lagoons, high emissions can result. Using digesters or otherwise treating manure can reduce these emissions

MITIGATION

Table 2: Summary of globally impactful interventions and estimated total carbon mitigation potential in GtCO2e/yr[47] and in parentheses $kgCO_2e/kg$ EW (beef) assuming current production levels.[48]

	Low	High
Carbon sequestration from improved grazing management	0.15 (2.3)	0.7 (10.6)
Improved feed digestibility (esp. forage)	0.12 (1.8)	0.7 (10.6)
Feed additives	0.2 (3.0)	0.3 (4.6)
Avoided LUC from intensification		0.25 (3.8)
Animal management (inc. reduced mortality, increased fertility, etc.)	0.1 (1.5)	0.2 (3.0)
Rangeland rehabilitation	0.1 (1.5)	0.15 (2.3)
Carbon sequestration from legume sowing		0.15 (2.3)
Manure management		0.1 (1.5)
Total	**0.67 (10.2)**	**2.55 (38.7)**

To the climate scientists, CH_4, N_2O, and CO_2 are greenhouse gases released into the atmosphere. However, for the livestock producer, these emissions are losses of energy, nutrients, and soil organic matter. Their emissions often reflect the inefficient use of inputs and resources.[49]

For both beef and dairy cattle production, management practices in different regions vary greatly in terms of stocking rate, cow size, calving season, primary forage types, and fertilizer application[50], so many interventions apply only to a subset of farms.

There are two focal areas for climate action in cattle: mitigation and sequestration. The former focuses on lowering emissions from key sources like enteric fermentation and manure, while the latter focuses on the potential to increase carbon stocks in the soil or biomass on lands grazed by cattle. As noted earlier, the quantification and accounting for sequestration on rangelands are not yet well

established, so most studies did not include the potential for sequestration in soil.

Prevent deforestation for pasture: Clearing forests for pasture is one of the leading drivers of global deforestation (responsible for 16% of global forest cover loss)[51] and likely between 0.5 and 1.5 $GtCO_2e$/yr total.

Improve grazing / rotational grazing: Improved, rotational grazing mitigates emissions by ensuring that cattle receive high quality forage and fast plant growth from quick bursts of grazing followed by recovery; this technique may also increase soil carbon. Herrero et al. estimated a global potential for improved grazing at 0.15 - 0.7 $GtCO_2e$/yr (roughly 2 - 11 $kgCO_2e$/kg EW based on current beef production levels);[52] this is broadly in agreement with Cusack's meta-analysis which found a 37% reduction in emissions for intensive rotational grazing[53] and with Roe et al.'s global analysis (0.13 - 2.56 $GtCO_2e$ soil carbon sequestration in grazing lands).[54]

Feed supplements: Feed supplements to reduce enteric fermentation have been the focus of much research, and commercial supplements have reached the market in Europe.[55] Other supplements, like algae,[56] show promise but are not currently commercially viable. How these supplements could be administered to grazed cattle is an open question that currently limits applicability to feedlot cattle. However, the potential emissions reductions are high (over 30% of methane reduced). Assuming a 30% reduction for 37 $kgCO_2e$/kg EW for mixed (pasture + grain-fed) cattle, the mitigation potential is globally about 0.5 $GtCO_2e$/yr; however, such supplements are likely not feasible for most farmers globally and improved feed digestibility is the first step.

Breed raised: Improved breeds can have superior performance. For breeds selected for high weight gain relative to enteric fermentation, GHG footprint reductions of 30% were found.[57] Given the relatively few studies conducted, it is unclear how representative this value is.

TOOLS & DATA AVAILABILITY

The GHG footprint of cattle is well characterized in the literature, as are the common feed ingredients used. The footprint from land-use change and from potential pasture sequestration is, however, highly variable and uncertain, respectively.

Given that the majority of emissions for cattle occur on-farm, a selection of farm-focused GHG calculators is highlighted here:

- **Cool Farm Tool:** an online tool produced by the Cool Farm Alliance that allows farmers to specify animal feed intake, composition, growth, and manure management to calculate a GHG footprint. The footprints are not regionally tailored, but the tool works globally. The results are particularly sensitive to the feed intake.
- **GLEAM-i:** an online tool produced by the Food and Agriculture Organization based on the Global Livestock Emissions Assessment Model. This tool can capture backyard and commercial production with default values for each country. The tool input asks for vital rates (rather than feed intake and animal numbers) which may make usage difficult.
- **Feedprint:** a stand-alone tool focused on emissions embedded in animal feed; there are a huge number of feed compositions and sourcing locations available. These feed ingredients can be tailored. The tool is geared toward Europe but has sourcing from many locations globally. On-farm emissions can also be calculated in the tool.
- **National tools:** many countries have nationally specific calculators that include poultry and feeds. For example, Comet-Farm for the US and the Farm Carbon Toolkit for the UK.

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CITATIONS / FOOTNOTES (continued)

31 This issue of boundaries was described in Cusack et al., “Reducing Climate Impacts of Beef Production.” and encountered by the authors of this report.

32 Poore and Nemecek, “Reducing Food’s Environmental Impacts through Producers and Consumers.”

33 Gerber et al., “Tackling Climate Change through Livestock”; Poore and Nemecek, “Reducing Food’s Environmental Impacts through Producers and Consumers.”

34 Gerber et al., “Tackling Climate Change through Livestock”; Poore and Nemecek, “Reducing Food’s Environmental Impacts through Producers and Consumers.”

35 FAO, “FAO - GLEAM Global Greenhouse Gas Emissions from Livestock Summary Data.”

36 FAO.

37 Rotz et al., “Environmental Footprints of Beef Cattle Production in the United States.”

38 Nguyen, T. L. T., Hermansen, J. E. & Mogensen, L. Environmental consequences of different beef production systems in the EU. J. Clean. Prod. 18, 756–766 (2010).

39 Desjardins, R. et al. Carbon Footprint of Beef Cattle. Sustainability 4, 3279–3301 (2012).

40 For 2018, Food and Agriculture Organization (FAO), “FAOSTAT.”

41 Regional estimates from Gerber, GLEAM.

42 Goldman et al., “Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber.”

43 For 2018, Food and Agriculture Organization (FAO), “FAOSTAT.” Area under permanent pasture / meadow

44 FAO, “FAO - GLEAM Global Greenhouse Gas Emissions from Livestock Summary Data.”

45 Poore and Nemecek, “Reducing Food’s Environmental Impacts through Producers and Consumers.”

46 FAO, “FAO - GLEAM Global Greenhouse Gas Emissions from Livestock Summary Data.”

47 Herrero et al., “Greenhouse Gas Mitigation Potentials in the Livestock Sector”; Gerber, Henderson, and Makkar, *Mitigation of Greenhouse Gas Emissions in Livestock Production: A Review of Technical Options for Non-CO2 Emissions.*

48 Food and Agriculture Organization (FAO), “FAOSTAT.” Average 2015-2019 for cattle meat.

49 Gerber et al., “Tackling Climate Change through Livestock.”

50 Zilverberg et al., “Energy and Carbon Costs of Selected Cow-Calf Systems.”

51 Goldman et al., “Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber.”

52 Herrero et al., “Greenhouse Gas Mitigation Potentials in the Livestock Sector”; Gerber, Henderson, and Makkar, *Mitigation of Greenhouse Gas Emissions in Livestock Production: A Review of Technical Options for Non-CO2 Emissions.*

53 Cusack et al., “Reducing Climate Impacts of Beef Production.” reported at 37% decrease in emissions, which of the roughly 63kgCO2e/kgEW (excluding emissions from LUC from pasture expansion) reported by GLEAM for grassland cattle, this means ~23kgCO2e/kgEW avoided. Multiplied by 33% of beef production, this yields about 0.5GtCO2e/yr mitigated emissions.

54 Roe et al., “Contribution of the Land Sector to a 1.5 °C World.”

55 For example, DSM’s Bovaer currently claims to reduce methane by 30% in dairy cows and 90% for beef cattle.

56 Kinley et al., “Mitigating the Carbon Footprint and Improving Productivity of Ruminant Livestock Agriculture Using a Red Seaweed”; Roque et al., “Red Seaweed (Asparagopsis Taxiformis) Supplementation Reduces Enteric Methane by over 80 Percent in Beef Steers.”

57 As reviewed in: Cusack et al., “Reducing Climate Impacts of Beef Production.”