CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF REGIONALLY PRODUCED BEEF IN THE NORTHWESTERN U.S.

D. J. Roop, D. S. Shrestha, D. A. Saul, S. Newman

ABSTRACT. *This article presents a life cycle assessment (LCA) performed on a regional beef production system. The analysis includes data for a cow-calf operation, six animal feeding operations, and a beef processing operation within the Pacific Northwest region consisting of Washington, Oregon, Idaho, western Montana, western Wyoming, northern California, northern Nevada, and southern British Columbia. The objective of this study was to determine the greenhouse gas (GHG) emissions associated with beef production on a regional scale in the identified area. This analysis was important for determining the comparative sustainability of beef production methods in the Pacific Northwest. The LCA defined the GHG emissions associated with two separate functional units from two distinct system boundaries. System boundary 1 (SB1) delineates a cradle-to-feedlot-gate analysis of the system and has a functional unit of 1 kg of live weight (LW) beef production. System boundary 2 (SB2) defines a cradle-to-processing-gate analysis of the system and has a functional unit of 1 kg of packaged beef. These estimates are used as indicators of the environmental burden of the given system in the given region. Total emissions from SB1 and SB2 were found to be 10.40 ±0.48 kg CO_2e kg^{-1} LW and 18.75 ±0.86 kg CO_2e kg^{-1} beef, respectively.*

Keywords. *Beef, GHG, Ranches, Small farms.*

This article presents a life cycle assessment (LCA) of a Pacific Northwest (PNW) beef production system. The objective of this research was to determine the greenhouse gas (GHG) emissions, primarily methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (NO_x), associated with beef production on a regional scale. This type of analysis is important for determining the sustainability of regional beef production systems compared to larger or smaller scale systems. The LCA reported in this article is one component of a multidisciplinary project that examined whether increased production and processing of livestock for local and regional markets would benefit rural areas of northern Idaho and eastern Washington. The project explored the feasibility, economics, and environmental impacts of several processing options for small and medium-sized livestock operations. The options were developed as scenarios that included small livestock operations that used small-scale USDA-inspected options for processing and a regional scenario that included small and medium-sized livestock operations supplying animals to a regional-scale feedlot and processing system. The results of the LCA for small-scale livestock production and processing were reported by Roop et al. (2014). This article presents results for the regional-scale production and processing supply chain.

Most published cradle-to-gate LCA studies have reported carbon dioxide equivalent (CO_2e) emissions as an indicator of environmental burden (Beauchemin et al., 2010; Casey and Holden, 2006; Cederberg and Stadig, 2003; Nguyen et al., 2010; Ogino et al., 2004; Pelletier et al., 2010; Phetteplace et al., 2001; Veysset et al., 2010; White et al., 2010). Results from these studies ranged from approximately 8.9 (Cederberg and Stadig, 2003) to 15.5 (Phetteplace et al., 2001) kg CO_2e kg^{-1} live weight of beef. This range shows that the differences in system type and modeling affect the outcome of the study and provides context for the results presented in this article.

DESCRIPTION OF THE BEEF PRODUCTION SYSTEM

The U.S. beef production system is made up of trucking, distribution, and feed production companies, large-scale producers, and many small-scale ranching and processing operations. Figure 1 illustrates a generalized system model of conventional beef production. In this system, beef begin their life in a cow-calf operation (CCO) where they are raised from birth to 6 to 12 months, depending on the operation and beef type. Pasture grazing is generally the main source of feed at CCOs; however, supplemental feed is often used during winter months where forage is scarce. Once calves are weaned, they are transported either to a backgrounding facility or a feedlot. A backgrounding facility is a small feedlot where animals can be treated more individually than is possible in a larger feedlot. The purpose of backgrounding is to normalize beef weights and

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Submitted for review in November 2013 as manuscript number SE 10498; approved for publication by the Structures & Environment Division of ASABE in April 2014.

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Transactions of the ASABE

Vol. 57(3): 927-935 © 2014 American Society of Agricultural and Biological Engineers ISSN 2151-0032 DOI 10.13031/trans.57.10498

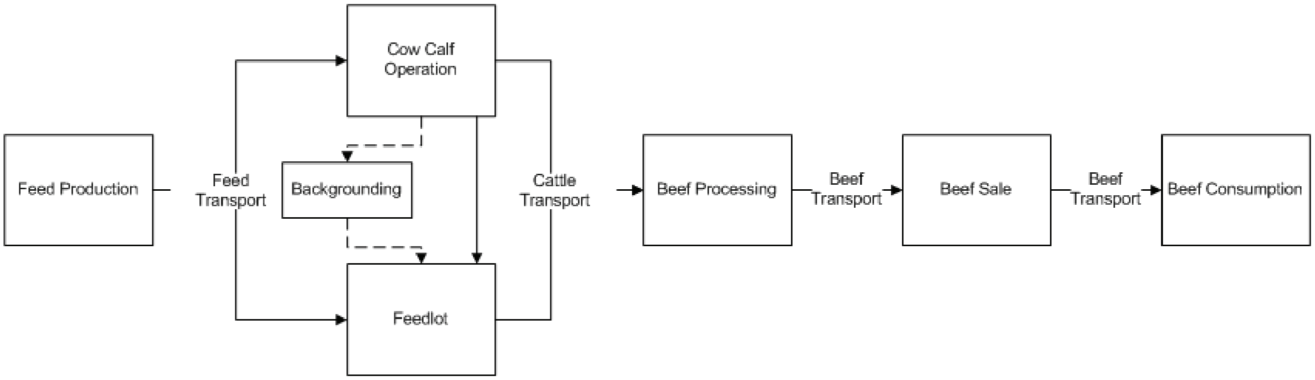

Figure 1. Generalized system model of conventional beef production.

prepare them for feeding in a feedlot. Feedlots are also known as animal feeding operations (AFOs), which are defined by the EPA (2003) as operations that confine animals for at least 45 days per year and have no grass or other vegetation in the confinement area. Feedlot beef are given a variety of feeds depending on region and availability, including corn and potato products (Adom et al., 2012).

Once beef reach a mature weight (545 to 680 kg depending on breed), they are transported to a processing facility. At this stage, the animals are slaughtered and butchered, and the beef is packaged for sale to the consumer. Beef can either be sold directly to consumers by the processing facility or it can be sold to a distribution center such as a grocery chain.

Some small and specialty operations differ from the conventional beef production chain by keeping beef on pasture throughout their life cycle, which generally takes longer than in feedlots. This process appeals to consumers who are willing to pay a premium for what they perceive as contributing to ethical animal treatment or improved human health (Tonsor and Olynk, 2011).

While many subregions exist within the PNW, most beef production is channeled into a common processing chain. Our study region encompasses Washington, Oregon, Idaho, western Montana, western Wyoming, northern California, northern Nevada, and southern British Columbia. While small-scale and specialty operations exist in the region, the system predominantly represents conventional beef production where large amounts of beef are processed and beef feeding operations are geographically concentrated. Beef production operations in the PNW are located in close proximity to other conventional agriculture operations. This allows use of a range of regionally available feed inputs, such as potato processing byproducts, including culled french fries and slurry (Kellems and Church, 2009).

METHODOLOGY

ORGANIZATIONAL AND SYSTEM BOUNDARIES

In this LCA, we examined the GHG emissions associated with two functional units: 1 kg of live weight (LW) beef production and 1 kg of packaged beef from a regional beef production system. The first functional unit (1 kg LW beef) is consistent with the cradle-to-feedlot-gate analysis of the local PNW beef production system conducted by Roop et al. (2014). This functional unit was used because, per federal regulation (HACCP, 2012), beef cannot be sold after slaughter without federal or equivalent inspection. Many local producers choose to sell live beef rather than seeking out USDA-inspected meat processing facilities. The second functional unit (1 kg of packaged beef) is a cradle-to-processing-gate analysis of the system.

The PNW system is primarily focused on beef rearing and processing. We chose one of the predominant beef production chains in the region for this study. The LCA includes analysis of one CCO located in the region, six AFOs located in Idaho and Washington, and one beef processing operation (BPO) located in Washington. The specific number and location of CCOs is unknown, and it is not possible to analyze all CCOs in the system. Because of a lack of data describing CCOs, the literature values in table 1 were used to estimate emissions associated with the rearing of beef from birth to ranch gate. The CCO that we analyzed supplies beef to AFOs in the regional system and was used to validate the literature values.

Based on an interview with animal procurement personnel working for the AFOs, an estimated 20% of beef come to AFOs via direct transaction with ranchers, 10% of beef come from video auction, and 70% of beef come through order buyers (i.e., third-party entities that obtain beef at a price set by the AFOs). Beef from direct transaction and video auction can be tracked fairly easily, but beef purchased through order buyers cannot. Order buyers act as middlemen between CCOs and AFOs and do not normally disclose the sources of their beef. Furthermore, the animal procurement personnel estimated that 60% of beef purchased by the feedlots in the PNW system are transported less than 160 km (100 mi) from CCOs to AFOs, 30% are transported between 160 and 560 km (100 and 350 mi), and 10% are transported longer distances.

Table 1. Literature values for cradle-to-gate CCO emissions.

Source	Cow-Calf Emissions (kg CO$_2$e kg^{-1} LW)
Phetteplace et al. (2001)	35.00[a]
Casey and Holden (2006	9.66, 15.36, 9.19, 14.68, 7.99, 13.81[b]
Nguyen et al. (2010)	6.60 to 11.40)[c]
Pelletier et al. (2010)	10.50, 10.55, 12.50
This CCO analysis	6.96

[a] Units are kg CO$_2$e kg^{-1} live weight gain.

[b] Emissions from six conventional farms studied.

[c] Range reported from three farms.

The studied BPO is supplied by more AFOs than the six included in this study. Conversely, the six AFOs also supply beef to other BPOs. Therefore, all emissions from the processing facility and AFOs were allocated according to the proportion of beef input or output included in the system boundary (fig. 2). Unless otherwise specified, all allocation in this analysis was done on a mass basis. Figure 2 is a graphical representation of the system boundaries and indicates where allocation was necessary. The output of beef from the processing facility shown in figure 2 only accounts for beef supplied by the AFOs included in our analysis (AFOs 1 through 6).

As figure 2 illustrates, our analysis includes two system boundaries. System boundary 1 (SB1) delineates a cradle-to-feedlot-gate analysis of the system, including:

- GHG emissions associated with utility use at CCOs and AFOs.
- GHG emissions associated with vehicle fuel use at CCOs and AFOs.
- GHG emissions associated with the production of feed used at CCOs and AFOs.
- GHG emissions associated with transport of beef from CCOs to AFOs and feed from point of origin to CCOs and AFOs.

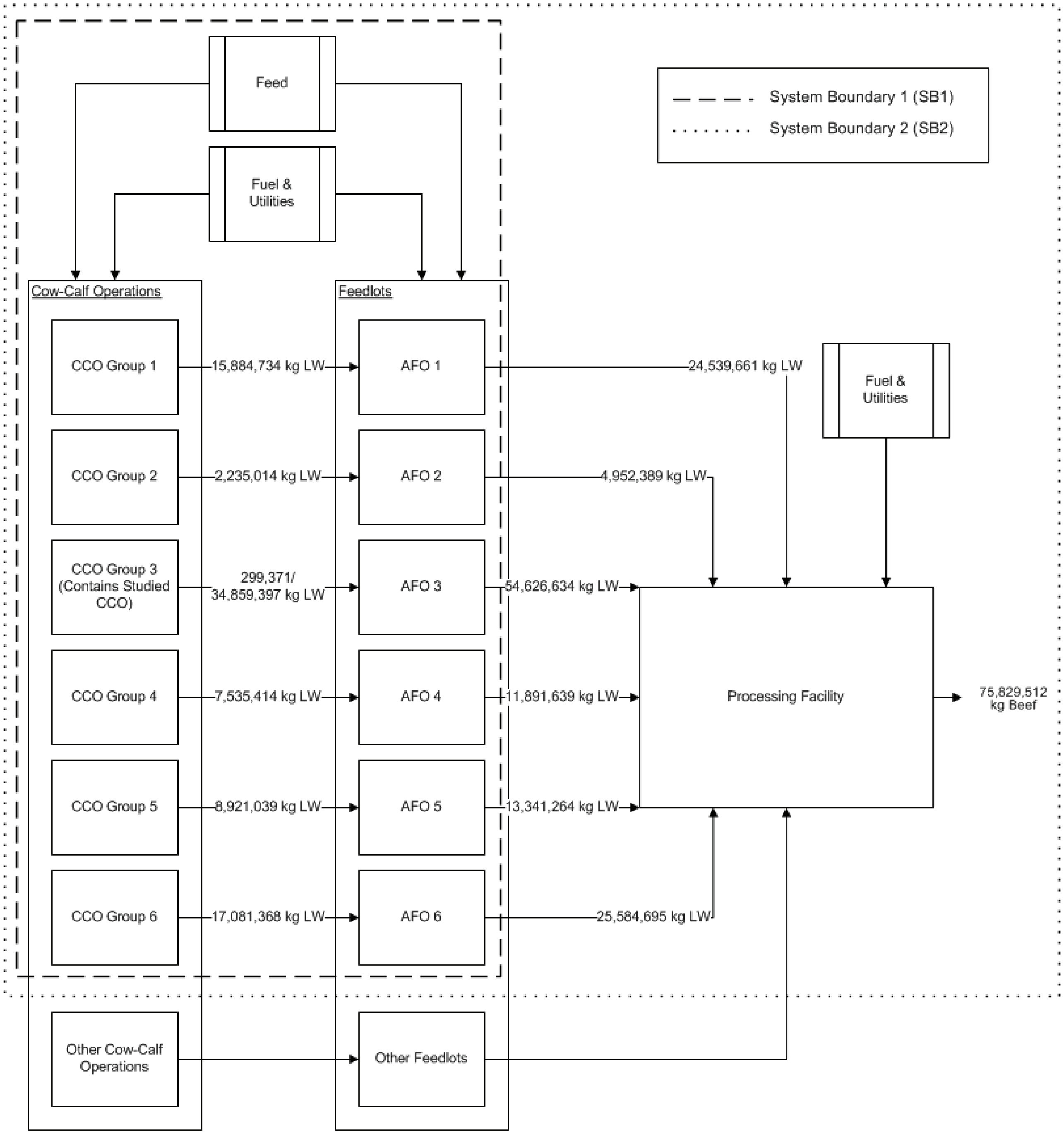

Figure 2. System boundaries, beef and beef product flows.

- Enteric fermentation emissions (CH_4) from beef at CCOs and AFOs.
- Manure management emissions from beef at CCOs and AFOs.

System boundary 2 (SB2) contains all aspects of SB1 and additional processing operations. Specifically, SB2 includes all emissions from SB1 as well as GHG emissions associated with the transport of beef from AFOs to the processing facility and fuel and electricity use at the processing facility.

DATA COLLECTION

Most data used in this analysis were measured and obtained from the CCO, AFOs, and BPO included in the study. We analyzed a single year of data (2006-2007) to provide a snapshot of emissions in that year. (Multiple years of measurement were available for some data sets. However, because not all data sets included multiple years, we used data from 2006.) The following types of data were provided:

CCO Data

- Fuel, utilities, and beef data, including number of beef produced, beef shipments (number of beef sent to studied feedlots), and fuel and utility use.

AFO Data

- Commodity location details, including amounts and ingredients fed, and vendor information for feed transport (location and amount purchased from each vendor).
- Beef shipments from each AFO, including ship date, head shipped, destination, days on feed, and initial and final weights.
- Fuel and utilities use (excluding fuel used for transport).

Processing Data

- Sales data (sales by shipment), including shipment dates, destinations, weights, and method of shipment.
- Fuel and utilities use at processing facility (excluding fuel used for transport).
- Source of beef shipments to the BPO, including AFO locations and amounts of beef shipped to the processing facility from each location.

Some data necessary for the LCA were not included in the 2006 data sets provided by the CCO, AFOs, or BPO. These included operational data from the CCO (e.g., beef numbers, feed types, and amounts), transport distances from the CCO to AFOs, and beef weights in some circumstances. We estimated CCO emissions using the literature values in table 1. The literature values in table 1 describe emissions associated with beef rearing to pre-AFO weight. These values encompass CCO emissions, reflecting feeding and management at a CCO until calves were weaned, as well as transport, feeding, and management of calves at a backgrounding facility to pre-AFO weight. The study performed by Phetteplace et al. (2001) was not included in the CCO emission estimate because of a lack of uniformity of the units provided, which were kg CO_2e kg^{-1} LW gain instead of kg CO_2e kg^{-1} LW production. The distinction is that normalized emissions over live weight gain do not include the total weight of the animal, only the weight gained at each facility, leading to a higher estimate (table 1).

From the values in table 1, we estimated a distribution of CCO emissions for use in a Monte Carlo simulation. All values shown in table 1 were used with the exception of the estimate provided by Phetteplace et al. (2001). The resultant distribution was tested for normality using the Lilliefors test and found to be normal within a 95% confidence interval. The CCO analysis performed as a part of this study fell within the distribution, suggesting that the distribution was representative of emissions that might be expected to be generated by CCOs in our study region. The Monte Carlo simulation performed in MathCad was done by randomly sampling 1,000 values from within the estimated distribution and using these values to estimate the average contribution of emissions from CCOs.

Similarly, we estimated beef transport from the CCO to AFOs according to the distribution previously described: 60% of beef purchased by the feedlots in the PNW system are transported less than 160 km (100 mi), 30% are transported between 160 and 460 km (100 and 350 mi), and 10% are transported longer distances. Occasionally, beef transport weights were estimated when data were lacking. In these cases, unfed beef (pre-AFO) were estimated to weigh 363 kg (800 lbs) on average, and fed beef (post-AFO) were estimated to weigh 544 kg (1,200 lbs) on average. These estimates were based on average fed and unfed weights, which were present in the data.

The data were divided into three categories: CCO data, AFOs operational data, and BPO data. For each of these categories, data were collected from each operation, including fuel and utilities, beef input weights and amounts, beef output weights and amounts, and transport distance to the next stage in the system. Additionally, feed input (types and amounts of feed used) and feed sources were collected for the CCO and AFOs. Fuel data listed total annual volumes of gasoline and diesel used in each operation. Utilities data were given in total annual electricity use in kWh. Tables 2 and 3 present operational data for the regional system. Table 2 shows operational data, and table 3 shows general beef information by AFO.

DATA ANALYSIS

For LCA organization and analysis, we primarily used GaBi 4.0 LCA software (PE International, Stuttgart, Germany). We modeled specific components of the LCA using data from the literature, life cycle inventory (LCI) database information, and the 2006 Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). CO_2e emissions were determined and corrected to their 100-year global warming potential (GWP) relative to CO_2 using the 2001 Impact Assessment Method of the Institute of Environmental Science (CML) at Leiden University (Leiden, Netherlands).

The data were analyzed to determine the GHG emissions associated with the production of beef on a regional scale. Emissions were determined for five main categories: beef specific, feed production, fuel use, utilities, and transport. This breakdown was done so that areas emitting higher levels of GHGs could be identified.

Table 2. Summary of operational data provided for analysis.

	CCO	AFO 1	AFO 2	AFO 3	AFO 4	AFO 5	AFO 6	BPO
Feed use (kg)								
Clarifier	-	-	19,440,941	-	-	-	-	-
Corn	-	37,656,063	17,874,882	22,799,770	5,261,488	5,539,083	7,011,910	-
Dry corn	1,154,223	13,874,682	-	37,802,362	9,049,500	9,254,135	60,207,521	-
DDGS	-	11,378,138	-	22,131,306	5,251,429	5,380,354	1,739,388	-
Forage	450,853	-	-	-	-	-	-	-
French fries	-	-	-	21,440,120	5,095,807	5,066,777	15,220,390	-
Hay	-	3,012,225	10,511,338	10,600,960	2,508,487	3,741,121	9,675,547	-
Screenings	-	-	5,930,567	-	-	-	17,788,311	-
Slurry	-	-	-	92,491,862	21,504,199	21,355,084	11,102,690	-
Soy meal and supp.	-	3,906,171	2,433,112	6,899,746	-	1,845,098	7,302,047	-
Tallow	-	2,161,870	-	1,838,312	426,553	374,480	-	-
Wet distillers grain	-	-	-	11,845,741	2,968,289	2,631,372	-	-
Wheat	-	13,977,448	17,549,225	19,360,646	4,460,191	4,425,820	-	-
Whey	-	9,815,533	-	-	-	-	-	-
Fuel use (MJ)								
Gasoline	1,438,751	591,442	662,653	1587,366	249,417	257,413	751,464	131,175
Diesel	6,65,566	3,875,483	3,510,488	9,570,892	1,764,347	2,070,225	24,690,012	1,218,271
Utilities (MJ)								
Electricity	1,799,986	2,586,032	1,502,675	5,823,859	866,997	928,104.6	2,527,623	61,562,298
Transport (kg-km)								
Feed	11,124,510	5.98E+09	6.34E+09	2.79E+10	6.99E+09	7.1E+09	1.32E+11	-
Beef from CCO	-	5.76E+09	8.06E+08	1.27E+10	2.72E+09	3.22E+09	6.79E+09	-
Beef to BPO	-	1.17E+10	3.57E+09	9.89E+09	2.07E+09	2.6E+09	4.62E+09	-

Table 3. General beef information for AFOs.

	AFO 1	AFO 2	AFO 3	AFO 4	AFO 5	AFO 6
Number of head	43,272.00	7,371.00	19,316.00	92,508.00	24,302.00	87,114.00
Average weight gain (kg)	199.17	374.43	226.20	212.62	185.31	190.74
Average days on feed	139.04	455.77	145.48	142.72	134.55	156.00
Average winter days	22.26	10.80	21.99	20.42	21.14	43.08

Beef-Specific Emissions

Beef emissions were calculated according to the 2006 Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). This method provided estimates for CO_2e emissions from enteric fermentation (CH_4) as well as CO_2e and nitrous oxide (N_2O) emissions from manure management. The Tier 2 approach was used for CO_2e estimates from enteric fermentation and manure management. The Tier 1 method was used to estimate N_2O emissions from manure management. Relevant coefficients used in the equations are listed in table 4.

Monthly enteric fermentation and manure management emissions at CCOs were determined separately for bulls, cows, and calves and then multiplied by the respective numbers of beef for each month in 2006. For calves, monthly weight gains were determined using the difference between birth and weaning weights divided by the weaning age. Zero weight gains were assumed for mature bulls and cows.

AFO beef emissions were estimated using the days that each animal spent at the facility in combination with the implemented feeding regimes. Beef were not segregated by gender or age for analysis of AFOs due to lack of data. However, specific weight gains and feed amounts were available for each group. Beef within each of these groups were treated equally in the analysis. All operations reported managing manure using passive windrow composting.

Feed Production Emissions

Emissions from feed production were primarily obtained from literature and life cycle inventory (LCI) database sources (table 5). Several feed sources were combined with similar feed sources due to a lack of separate data describing their production. The combination of sources resulted in 13 feed categories. The categories, sources, and emissions are listed in table 5. Feed categories containing only one feed type were clarifier, dry corn, french fries, screenings, slurry, tallow, wet distillers grain, and whey. Cobbage, corn, and high-moisture corn were combined because they are similar in emissions. Corn syrup was combined with dry distillers grain with solubles (DDGS) because DDGS contains corn syrup. Straw, which makes up only a minute portion of the feed mixture for AFO 5, was com-

Table 4. Coefficients used for IPCC cattle emissions calculations (IPCC, 2006).

IPCC Table	Table Name	CCO / AFO Values
10.2	Representative feed digestibility for various livestock categories (DE%)	65% / 80%
10.5	Activity coefficients corresponding to animal feeding situation (C_a)	0.00 or 0.17[a] / 0.00
10.12	Cattle/buffalo CH_4 conversion factors (Y_m)	0.00 or 0.075[b] / 0.03
10 A-5	Manure management methane emission factor derivation for other cattle (B_o)	0.19 / 0.19
10.21	Default emission factors for direct N_2O emissions from manure management	0.01 / 0.01
10.22	Default values for nitrogen loss due to volatilization of NH_3 and NO_x from manure management	30% / 30%

[a] During winter months, animals were considered to be fed in a stall situation ($C_a = 0.00$);
during non-winter months, animals were considered to be fed in a pasture situation ($C_a = 0.17$).

[b] A Y_m value of 0.00 was suggested for calves prior to weaning; for all other cattle, a Y_m value of 0.075 was used.

Table 5. Feed categories, sources, and emissions.

Feed	Sources	Emissions or Energy Requirement
Clarifier	Somsen et al., 2004; Lamb Weston, 2011	0.0148 kg CO_2e kg^{-1}
Corn	U.S. LCI database, PE International	0.29 kg CO_2e kg^{-1}
Dry corn	Uhrig and Maier, 1992	12,589 BTU[a]
DDGS	Adom et al., 2012	2.3 kg CO_2e kg^{-1}
French fries	Somsen et al., 2004; Lamb Weston, 2011	0.3205 kg CO_2e kg^{-1}
Hay	Adom et al., 2012	0.15 kg CO_2e kg^{-1}
Screenings	Somsen et al., 2004; Lamb Weston, 2011	0.0728 kg CO_2e kg^{-1}
Slurry	Somsen et al., 2004; Lamb Weston, 2011	0.0635 kg CO_2e kg^{-1}
Soybean meal	Adom et al., 2012	0.41 kg CO_2e kg^{-1}
Tallow	Thamsiriroj and Murphy, 2011	1.8675 MJ[b] or 15.705 MJ[c]
Wet distillers grain	Adom et al., 2012	2.21 kg CO_2e kg^{-1}
Wheat	U.S. LCI database, PE International	0.4 kg CO_2e kg^{-1}
Whey	Gerber et al., 2010	0.02 MJ[d]

[a] Energy requirement for drying one bushel of corn from 22% to 15% moisture content.
[b] MJ electricity requirement kg^{-1} tallow.
[c] MJ steam requirement kg^{-1} tallow.
[d] MJ energy requirement kg^{-1} whey.

bined with hay because of a lack of data for emissions from straw production. Millrun, wheat, and wheat middlings were combined into one emissions category because they are all products or byproducts of wheat milling. Since the byproducts (millrun and wheat middlings) are estimated to have the same emissions as wheat, this overestimated their contribution; however, they are fed in such low quantities that this is not a concern. Finally, feeds lacking emissions data for proprietary reasons (arrival, finish, and heifer finish supplements) or those fed in extremely small amounts (less than 0.5% of overall feed by weight), such as molasses, were excluded from the analysis. These feed types together made up less than 5% of total feed by weight for each AFO. The small proportion of total feed contributed by these feed types was estimated to have emissions equal to the average emissions from other feed categories.

AFOs 3, 4, and 5 used significant amounts of potato processing byproducts in their feed mixes. These byproducts included clarifier, french fries, screenings, and slurry. Screenings, also known as screen solids, contain small pieces of uncooked potato and are a byproduct of size screening done before french fries are cooked. French fries as a feed refers to cooked culls from french fry production. Slurry and clarifier are both byproducts of french fry production. Slurry is a byproduct of primary wastewater treatment, while clarifier is a byproduct of secondary treatment or clarification. Allocation methods and calculations for potato processing byproducts and tallow are given in the following paragraphs. Figure 3 shows the mass output of byproducts from potato processing (Somsen et al., 2004). At this time, no alternative use of potato byproducts is available in the area; if they were not used for beef feed, they would be disposed of in a solid-waste landfill. No attempt to discount emissions from byproducts was made as part of this study, although doing so would certainly be valid. Further analysis to determine an accurate discounting method and factor would likely significantly reduce the emissions contributed by potato byproducts.

Potato Processing Byproducts: Emissions were allocated among byproducts on a mass basis. Below are sample calculations for screenings. Estimated emissions from finished products of potato processing are 0.283 kg CO_2e kg^{-1} product (french fries) for production alone (Lamb Weston, 2011). Following the mass basis allocation, the same emissions for all co-products were assumed. As discussed earlier, no discounting for byproducts was made in this analysis based on their economic values. This is to make the results more consistent and is preferred by several researchers (Pradhan et al., 2008).

Tallow Production: Along with meat and bone meal, tallow is a byproduct of animal slaughter and meat production. Tallow is produced by rendering animal byproducts (ABPs). We estimated that tallow makes up 16% of the byproduct stream by weight. Furthermore, we estimated that the production of ABPs uses approximately 83 kWh of electricity per metric ton (t) of ABP and 698 kWh of steam energy per metric ton of ABP (Thamsiriroj and Murphy, 2011). The energy requirements for tallow are calculated with the following equations:

Electricity:

$$\left(83\frac{\text{kWh}}{\text{t ABP}}\right)\times\left(\frac{1}{0.16}\frac{\text{t ABP}}{\text{t tallow}}\right)\times\left(0.001\frac{\text{t}}{\text{kg}}\right)\times\left(3.6\frac{\text{MJ}}{\text{kWh}}\right)=1.8675\frac{\text{MJ}}{\text{kg tallow}}$$

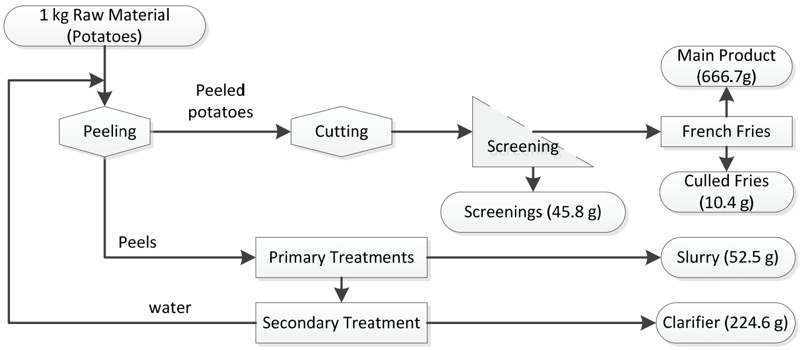

Figure 3. Mass allocation of potato byproducts.

Steam:

$$\left(698\,\frac{\text{kWh}}{\text{t ABP}}\right)\times\left(\frac{1}{0.16}\,\frac{\text{t ABP}}{\text{t tallow}}\right)\times\left(0.001\frac{\text{t}}{\text{kg}}\right)$$
$$\times\left(3.6\frac{\text{MJ}}{\text{kWh}}\right)=15.705\frac{\text{MJ}}{\text{kg tallow}}$$

Fuel and Utility Emissions

The amounts of gasoline and diesel fuel used at each operation were included in this study. Emissions from the production, transportation, and use of these fuels were determined using the PE International U.S. LCI database. Utilities were analyzed similarly. Data for utilities were provided in kWh of electrical use at each facility for 2006. Emissions associated with electricity production, transportation, and use were determined using PE International database processes (included in GaBi 4.0) for U.S. electricity consumption for the Mountain and Pacific regions.

Transport Emissions

In all cases that transport was included in the study, shipment measurement units (kg-km) were calculated from three separate measurements: shipping load (kg trip^{-1}), number of shipments (trips), and shipping distance (km). Shipment measurement units were calculated for feed shipped to the case study CCO, feed shipped to the AFOs, beef shipped to the AFOs, and beef shipped to the processing facility. Once shipment units were calculated, the PE International U.S. LCI database was used to calculate emissions associated with transportation.

RESULTS AND DISCUSSION

We analyzed the PNW regional beef production system according to two system boundaries (SB1 and SB2). For AFOs, feed production was the main contributor to emissions, accounting for 60% to 79% of emissions from AFOs. For the CCO, enteric fermentation and manure management were the greatest GHG emission contributors. Table 6 provides normalized emissions for the CCO along with known values from the AFOs and BPO. The CCO analysis resulted in total GHG emissions of 6.96 kg CO_2e kg^{-1} LW. This value fell within the range of the literature values in table 1. Table 6 lists emissions from each studied operation normalized over the live weight (or product) output from that operation.

With the exception of AFOs 2 and 6, little variation occurred in beef emissions (enteric fermentation and manure management) and beef transport emissions, while other categories such as fuel use varied much more significantly. AFO 2 and AFO 6 generally had higher normalized emissions due to longer beef residence times at those facilities. The reason for the longer residence times at AFOs 2 and 6 are unknown.

The CCO analysis and other CCO emissions estimates from the literature were used to perform a Monte Carlo simulation to determine overall emissions from SB1 and SB2. The Monte Carlo simulation was performed primarily in MathCad with literature values for CCO emissions to generate a normal distribution. A total of 1,000 random values (kg CO_2e kg^{-1} LW) were pulled from the constructed distribution and multiplied by the live weight input values for each AFO in figure 2. The resulting total emission values for beef entering each AFO were combined with the data in table 6 to determine overall emissions from beef exiting SB1 and SB2. Table 7 presents the average total normalized system boundary emissions. The values reported in table 7 are averages of the six distinct feedlot opera-

Table 6. Normalized emissions from operations (units are kg CO_2e kg^{-1} LW unless specified otherwise).

	CCO	AFO 1	AFO 2	AFO 3	AFO 4	AFO 5	AFO 6	BPO[a]
Feed production emissions								
Clarifier	-	-	0.0581	-	-	-	-	-
Corn	1.5422	0.4504	1.0596	0.1225	0.1299	0.1219	0.0805	-
Dry corn	-	0.2476	-	0.3029	0.3330	0.3035	1.0300	-
DDGS	-	1.0665	-	0.9326	1.0156	0.9270	0.1564	-
Forage	0.2259	-	-	-	-	-	-	-
French fries	-	-	-	0.1258	0.1373	0.1217	0.1907	-
Hay	-	0.0184	0.3183	0.0291	0.0316	0.0421	0.0567	-
Screenings	-	-	0.0872	-	-	-	0.0506	-
Slurry	-	-	-	0.1075	0.1148	0.1016	0.0276	-
Soy meal and supplements	-	0.0653	0.2015	0.0518	0.0559	0.0568	0.1170	-
Tallow	-	0.1529	-	0.0580	0.0619	0.0488	-	-
Wet distillers grain	-	-	-	0.4791	0.5512	0.4355	-	-
Wheat	-	0.2298	1.4298	0.1430	0.1513	0.1338	-	-
Whey	-	1.1701	-	-	-	-	-	-
Fuel use emissions								
Gasoline	0.3545	0.0018	0.0099	0.0021	0.0015	0.0014	0.0022	0.0001
Diesel	0.1974	0.0140	0.0630	0.0156	0.0132	0.0138	0.0857	0.0010
Utility emissions								
Electricity	1.5372	0.0269	0.0776	0.0273	0.0186	0.0178	0.0253	0.1508
Transport emissions								
Feed	0.0035	0.0228	0.1196	0.0476	0.0549	0.0497	0.0842	-
Beef from CCO	-	0.0219	0.0152	0.0218	0.0214	0.0226	0.0248	-
Beef to BPO[a]	-	0.0083	0.0025	0.0071	0.0015	0.0019	0.0033	-
Beef emissions								
Enteric fermentation	2.3305	0.6002	1.1764	0.6010	0.6139	0.5712	0.6263	-
Manure management	0.7738	0.2235	0.6318	0.2259	0.2303	0.2153	0.2493	-

[a] Units are kg CO_2e kg^{-1} packaged beef.

Table 7. Total emissions for SB1 and SB2.

System Boundary	Average Emissions	SE	Units
SB1	10.40	0.19	kg CO_2e kg^{-1} LW fed beef
SB2	18.75	0.34	kg CO_2e kg^{-1} packaged beef

tions. Therefore, the standard error (SE) was calculated with a sample size of $n = 6$.

Feed emissions comprised a significant portion of emissions from AFOs. Figure 4 shows the percentage of mass associated with each feed type compared to the percentage of emissions associated with each feed type by AFO. Some feeds, such as potato slurry, were fed in large quantities but contributed only minimally to feed emissions. Other feeds, such as DDGS, were fed in small amounts but resulted in large emissions.

The main source of uncertainty comes from the lack of data describing the CCOs in our study region. We attempted to compensate for the lack of data by using a Monte Carlo simulation to estimate the emissions contributed by CCOs. Uncertainties within the Monte Carlo simulation could account for less than 1% of the variations in the reported average emissions.

CONCLUSION

In this life cycle assessment, we investigated the emissions associated with regionally produced beef in the Pacific Northwest. Our assessment included data from one cow-calf operation (CCO), six animal feeding operations (AFOs), and one beef processing operation (BPO). The AFOs produced approximately 22 million live weight pounds of beef per AFO annually. We analyzed and reported the greenhouse gas (GHG) emissions associated with five main categories: beef-specific emissions, feed production emissions, fuel use emissions, utilities emissions, and transport emissions. This breakdown was done to identify areas emitting higher levels of GHGs.

Two system boundaries were used. System boundary 1

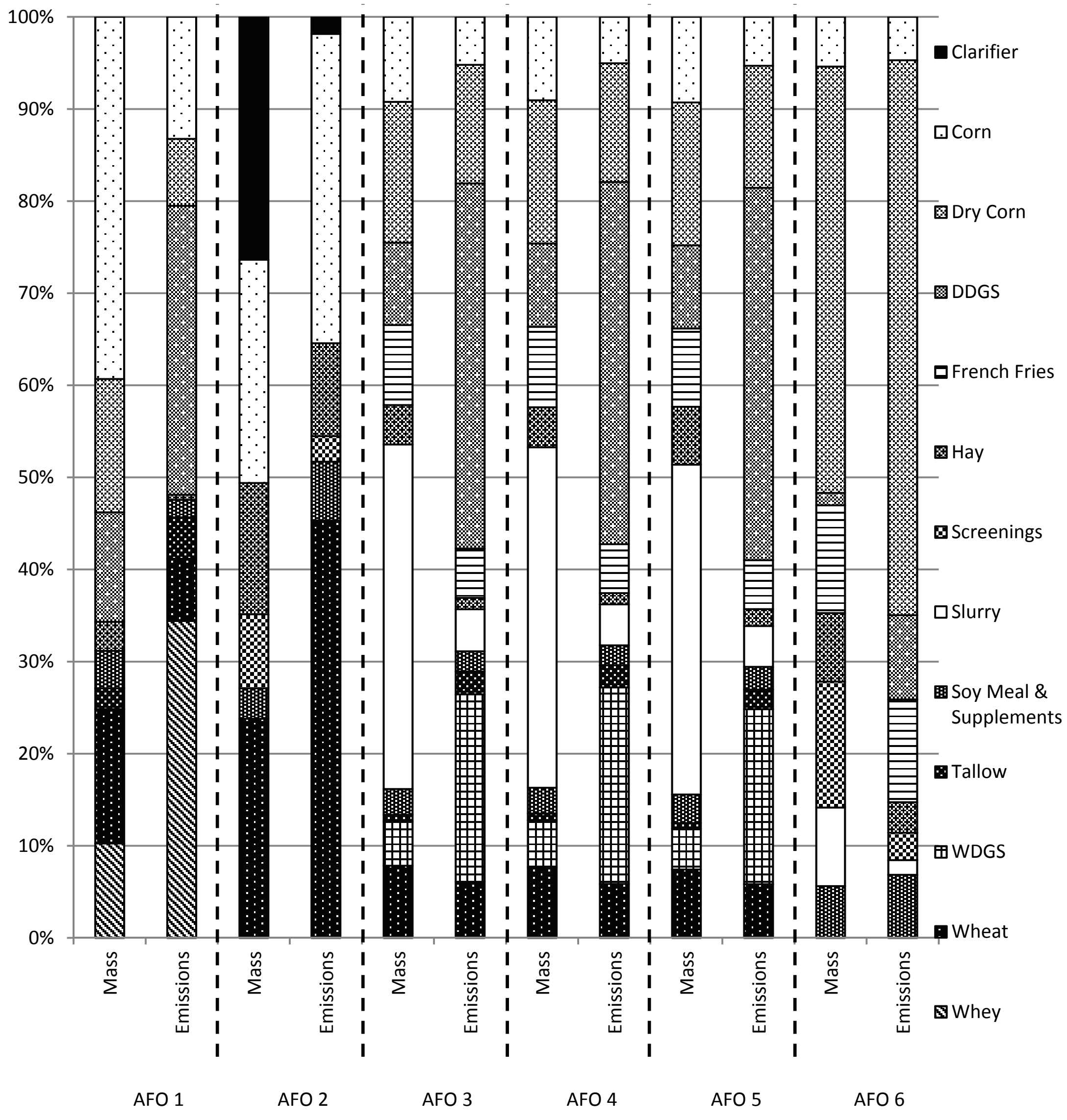

Figure 4. Compositions of feed vs. feed emissions from animal feeding operations.

(SB1) delineates a cradle-to-feedlot-gate analysis of the system, and system boundary 2 (SB2) delineates a cradle-to-processing-gate analysis of the system. Functional units of 1 kg live weight (LW) and 1 kg packaged beef were used for SB1 and SB2, respectively. Total emissions from SB1 were found to be 10.40 ±0.48 kg CO_2e kg^{-1} LW; total emissions from SB2 were found to be 18.75 ±0.86 kg CO_2e kg^{-1} beef. The confidence interval of the mean was calculated from the SE in table 7 assuming a t-distribution, a 95% confidence interval, and five degrees of freedom. These emissions fall within the lower range of values identified in the literature. Emissions from SB1 were significantly lower than from local beef production in the Palouse region of eastern Washington and northwestern Idaho, which had associated emissions of 13.78 ±2.08 kg CO_2e kg^{-1} LW (Roop et al., 2014).

This analysis of a regional beef production system in the Pacific Northwest suggests that regional livestock production systems may be more environmentally sustainable than the alternatives of local, small-scale livestock production systems or conventional large-scale beef production systems.

ACKNOWLEDGEMENTS

We thankfully acknowledge the support of the Agriculture and Food Research Initiative of the National Institute of Food and Agriculture.

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