6-3-2019

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Li, Shaobin; Subbiah, Jeyamkondan; and Dvorak, Bruce, "Environmental and occupational impacts from U.S. beef slaughtering are of same magnitude of beef foodborne illnesses on human health" (2019). *Biological Systems Engineering: Papers and Publications*. 621.
https://digitalcommons.unl.edu/biosysengfacpub/621

Environment International 129 (2019) 507–516

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Environmental and occupational impacts from U.S. beef slaughtering are of same magnitude of beef foodborne illnesses on human health

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ARTICLE INFO

Handling Editor: Frederic Coulon

Keywords:
Environmental human health
Foodborne illness
Life cycle assessment
Occupational hazards
U.S. beef sustainability

ABSTRACT

Foodborne pathogens and occupational hazards are two primary safety concerns for U.S. beef slaughterhouses. The anthropogenic environmental impacts due to intensive resource use and pollution also exert threats to human health. Quantifying human health impacts from various sources remain a grand sustainability challenge for U.S. beef industry. We develop a framework to systematically estimate and compare human health impacts associated with U.S. beef foodborne illnesses from major pathogens and environmental impacts and occupational hazards from U.S. beef slaughtering on a common metric, disability-adjusted life year (DALY). Foodborne illnesses and occupational hazards are estimated by synthesizing published data and methodologies while environmental impacts are quantified using life cycle assessment. In spite of inherent uncertainties in estimation, results show that the environmental impacts and occupational hazards from beef slaughtering are of same magnitude with foodborne illnesses from beef consumption on human health. *Salmonella* and *Clostridium perfringens* contribute 51% and 28%, respectively, to the beef foodborne DALY; Global warming and fine particulate matter formation, due to electricity and natural gas use, are primary drivers for environmental DALY, accounting 62% and 28%, respectively. Occupational DALY is on average lower than environmental DALY from beef slaughtering and foodborne DALY. The impact of new food safety interventions that use additional resources to improve food safety should be considered jointly with environmental impacts and occupational hazards to avoid unintended shifts and net increase of human health impacts. The methodology and results from this study provide a new perspective on reforms of the U.S. food safety regulations building toward sustainability in the food processing industry.

1. Introduction

Centers for Disease Control and Prevention (CDC) estimated that about 639,640 illnesses, 3075 hospitalizations, and 55 deaths caused by foodborne diseases in the U.S. annually are attributed to beef using foodborne outbreaks data between 1998 and 2008 (Painter et al., 2013). Disability-adjusted life years (DALY) is a metric proposed by the World Health Organization (WHO) to account overall disease burden associated with health problems, including years of life lost (YLL) due to mortality and years lost due to disability (YLD), with one DALY representing the loss of one healthy year (Murray and Lopez, 1996). The beef slaughtering stage has been a primary focus of food safety interventions. In a surveillance report from CDC for foodborne diseases outbreaks in the U.S. between 2009 and 2010, beef was the food that accounted the most foodborne outbreaks that connected food with ingredients from one of the seventeen predefined food commodities (CDC, 2013; Painter et al., 2013). Havelaar et al. investigated disease burden of foodborne diseases caused by fourteen leading pathogens using DALY and showed that beef disease burden ranking at the third largest contributor followed by pork and poultry in the Netherlands in 2009 (Havelaar et al., 2012).

One key step in preventing beef foodborne diseases through the beef supply chain lies in the slaughtering stage where various antimicrobial interventions are applied to minimize pathogenic contamination to the meat from beef hides and guts (Elder et al., 2000; Gansheroff and O'Brien, 2000). The U.S. Department of Agriculture (USDA) has enforced Hazard Analysis and Critical Control Points (HACCP) program to reduce the risk of foodborne outbreaks due to the insufficient food safety interventions and inappropriate sanitation practices (USDA FSIS, 1996). However, minimizing pathogenic contamination on beef

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https://doi.org/10.1016/j.envint.2019.05.051
Received 4 March 2019; Received in revised form 29 April 2019; Accepted 19 May 2019

products within slaughterhouses is at the expense of consuming intensive resources (water, energy, chemicals, etc.) (Hansen et al., 2000), producing high strength wastewater (Bustillo-Lecompte and Mehrvar, 2015) and solid waste (Peters et al., 2010) and posing occupational threats on workers safety (US Government Accountability Office, 2005). The illness and injury rates (i.e., cases per 100 full-time workers) for the meat industry are higher than that for other U.S. private industries (e.g., manufacturing, construction, retail trade), due to the exposure to dangerous machinery, toxic chemicals, greasy floors, pathogenic hazards, etc. (Bureau of Labor Statistics, 2016; Occupational Safety and Health Administration, 2017). Due to differences in the metrics, however, data of occupational injuries from BLS cannot be directly compared with other foodborne and environmental human health impacts.

The disease burden expressed in DALY has been adopted to evaluate impacts on human health in various industries (Dhondt et al., 2013; Dong et al., 2016; Heimersson et al., 2014). Environmental impacts on human health can be evaluated using life cycle assessment (LCA), an international standardized method (ISO14040-14044) for quantifying environmental impacts of products or systems from raw materials extraction, manufacturing, operation, and to its end of life (Jolliet et al., 2018). LCA has been widely applied in food production systems to assess their sustainability (Henriksson et al., 2018). However, there has not been detailed process-level LCA study for U.S. beef slaughtering industry. Heimersson et al. (2014) include pathogen risk with life cycle assessment to compare pathogen impacts with other environmental impacts on human health and have found pathogen risks can contribute up to 20% of total human health impacts from combined environmental and pathogenic risks in municipal wastewater treatment systems. Scanlon et al. introduce a methodology of integrating occupational hazards into account of life cycle assessment and demonstrate it in municipal solid waste treatment systems (Scanlon et al., 2015). The results show that occupational hazards contribute to 20% and 12% of total combined DALY from environmental and occupational health risks based on landfill and incineration, respectively. Those studies show the necessity and feasibility of evaluating human health impact from various sources in our society. However, none of the studies have investigated foodborne pathogen, environmental, and occupational impacts on human health together.

As global meat consumption is expected to increase and the U.S. beef is expected to play an important role of the global meat supply chain (Charles et al., 2018), advancing the sustainability of U.S. beef slaughtering is an important need. The overarching research question addressed is: What is the relative importance of the three impacts (i.e. beef foodborne illness, environmental impacts and occupational hazards from beef slaughtering) on human health? Most assessments of those impacts on human health are studied separately and do not offer a comprehensive view to fully understand the overall human health impact. Such a comprehensive assessment is especially important for the beef industry that currently focuses on effectiveness of food safety interventions but not as much on the environmental impacts on human health. With increasing consumers' interest in sustainable beef, a simultaneous assessment of all impacts is gaining interests. The overarching objective of this work is to develop a framework (described schematically in Fig. 1) for comparing disease burden expressed in DALY caused by foodborne illnesses from U.S. beef consumption, and environmental impacts and occupational hazards from U.S. beef slaughtering.

2. Methods

The schematic overview of the methodology for calculating these three sources of disease burden expressed in DALY were illustrated in Fig. 1. The concept of disability-adjusted life years (DALY) proposed by the WHO is used to compare human health impacts in this study. More details regarding DALY can be found in the original work (Murray and Lopez, 1996). For calculating the disease burden of foodborne illnesses and environmental impacts, we apply characterization-based method to estimate their disease burden. Specifically, the DALY per foodborne illness caused by various pathogens was estimated from literature and then applied to beef foodborne illness. The characterization factors of environmental impacts (e.g., DALY per kg pollutant emitted via different compartments) are obtained from well-establish impact assessment methods such as ReCiPe 2016 (Huijbregts et al., 2017) and USEtox 2.0 (Marian Bijster et al., 2017). For occupational hazards, DALY is calculated combining years of life lost (YLL) and years lived with disability (YLD). Details regarding on calculating the three sources of disease burden are described below.

2.1. Disease burden of foodborne illnesses from beef consumption

2.1.1. Attribution of foodborne illnesses caused by seven major pathogens

Disease burden of foodborne illnesses from beef consumption was estimated by combining findings from published studies on foodborne diseases. Annual foodborne illnesses related to beef consumption were retrieved from the findings of Painter et al. (2013) as shown in the Supplementary Information (SI) Appendix, Table S1.1. In Painter et al. (2013), all foodborne outbreaks reported to the CDC from 1998 to 2008 were reviewed and total annual US foodborne illnesses were attributed to 17 food commodities caused by 31 major pathogens (Scallan et al., 2011b). Nine pathogens among 31 major pathogens were linked to foodborne illnesses with beef and about 94% of foodborne illnesses related to beef was contributed by those seven leading foodborne pathogens (SI Appendix, Table S1.1).

2.1.2. Calculation of DALY per 1000 foodborne illnesses

DALY per 1000 cases of illnesses of each pathogen were calculated based on two studies evaluating human health foodborne impacts expressed in DALY. In this study, the characterization factor (i.e. DALY per 1000 cases) of seven major pathogens, accounting 94% of the nine pathogens, was available in the literature and thus considered in this study. Data on five pathogens (DALY per 1000 foodborne cases) were retrieved from the study focusing on the United States (Scallan et al., 2015), including *Clostridium perfringens, E. coli O157, Listeria monocytogenes, Norovirus*, *Salmonella.* The DALY data of other two remaining pathogens were *Bacillus cereus* and *Staphylococcus aureus,* obtained from the study focusing on Netherland (Havelaar et al., 2012).

The total YLD from the seven leading pathogens were determined including acute illnesses (e.g., acute gastroenteritis) and sequelae (e.g., Guillain–Barré syndrome, reactive arthritis, post-infectious irritable bowel syndrome). The total YLL from the seven leading pathogens was calculated by multiplying the number of deaths by remaining longevity at the time when death occurred. Calculating such YLD and YLL requires multiple data sources. More detailed information regarding methods and data sources can be found in the work of Scallan et al. (2015) The total YLD and YLL caused by the seven leading pathogens were then divided by the foodborne illnesses caused by each pathogen and normalized to 1000 foodborne illnesses, resulting in the unit of DALY/1000 foodborne illnesses (SI Appendix, Table S1.2). The number of foodborne illnesses was multiplied by the DALY/1000 illnesses to obtain the annual estimated DALY (SI Appendix, Table S1.3).

2.2. Disease burden of environmental impacts from beef slaughtering

2.2.1. Scope and system description

The environmental impacts on human health from beef slaughtering were estimated using LCA in SimaPro 8.4 LCA software (PRé Consultants, The Netherlands). The system boundary of the studied beef slaughterhouse consists of on-site resource usage (e.g. consumption of water, electricity, natural gas, wastewater treatment, chemical and packaging materials, solid waste generation). The environmental impacts account for downstream impacts such as solid waste transport and

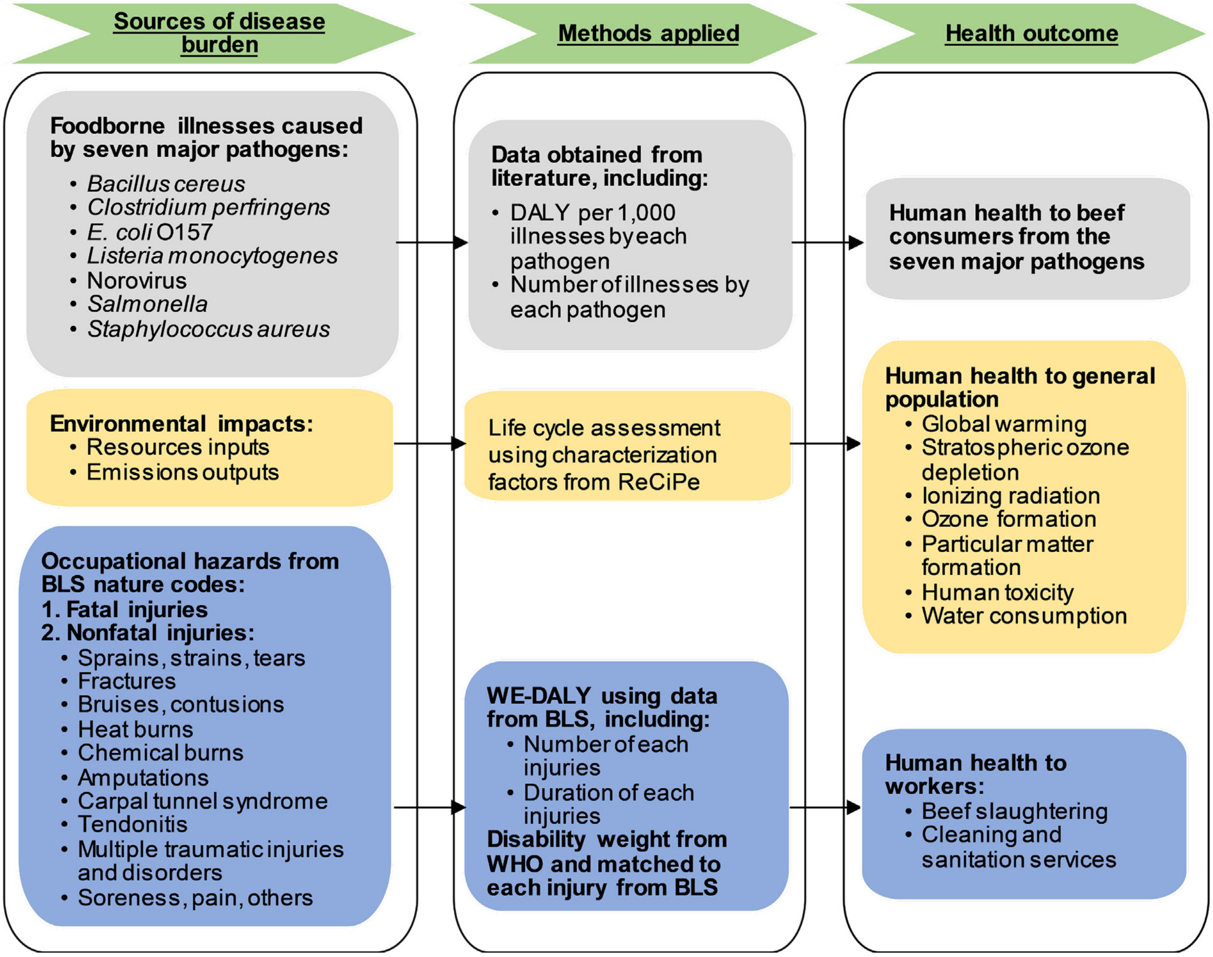

Fig. 1. Schematic view of the framework for determining disability-adjusted life year (DALY). The left panel introduces three impacts on human health: foodborne illnesses, environmental impacts, and occupational hazards. The middle panel presents methods applied to calculate the three impacts individually. The right panel shows the human health outcome expressed in DALY. Note: BLS = Bureau of Labor Statistics.

disposal and wastewater treatment, and those from upstream activities such as extraction and production of energy, chemicals, packaging and other materials. The term "slaughtering" used in this study includes the entire process flow diagram starting from receiving cattle until producing boxed beef cuts ready for shipping to retailers (Fig. 2). Cattle are delivered to the pen yard and driven to the kill floor where a series of slaughtering activities take place, including stunning, bleeding and blood separation, hide and head removal, evisceration, antimicrobial treatments, etc. The split carcasses are then sent to chilling room for 24–48 h before fabricating. In the fabrication floor, the spit carcasses are cut and deboned into primal cuts, such as chuck, rib, loin, etc. After fabrication, the beef products are packaged and stored under refrigeration.

2.2.2. Life cycle inventory

Inventory data on detailed process level were primarily obtained from two typical commercial beef slaughterhouses located in the Midwest of U.S., including all water, electricity, natural gas, packaging materials, chemical usage, solid waste (i.e. plastics, organic waste), and wastewater treatment associated with the beef slaughter process from within the plant's system boundaries. The energy consumption in beef slaughterhouse includes operational electricity use for refrigeration and equipment and thermal energy for steam production. The energy from equipment installation, such as refrigeration installations, is not considered in this study due to data limitation and energy of installation is assumed to be negligible compared to operational energy over 20 years life span (Morera et al., 2017). The chemicals applied in a beef slaughterhouse are used for cleaning, antimicrobial treatment, general processing, oils and lubricants. Environmental impacts of wastewater water treatment include onsite resources (e.g., energy, chemicals) in an industrial wastewater treatment plant specifically for treating slaughterhouse wastewater and the water quality of the effluent (Li et al., 2018a). The waterborne emissions of active ingredients of chemicals enter the wastewater plant for treatment. Inventory data were collected using a combination of methods, including onsite measurement, vendors' invoices, plant's utility bills and plant's discharge reports over two years (Li et al., 2018a, 2018b; Ziara et al., 2018). Detailed inventory data are provided in SI Appendix, Table S2.1.

Background database on the production of these resources and treatment of solid wastes are provided in SI Appendix, Table S2.2. Background database was obtained from US-EI 2.2 database (Long Trail Sustainability, 2016), a database that replaces Europe data with U.S. data in the ecoinvent database v3.3 (Wernet et al., 2016) wherever U.S. data are available. Specific processes data of rendering process and manure disposal and management are listed in SI Appendix, Tables S2.3 and S2.4, respectively. As this work focused on resource inputs and waste outputs during beef slaughtering, economic outputs of products (e.g., meat) and by-products (e.g., blood, bone, viscera) from beef slaughterhouse are not considered in this study.

2.2.3. Life cycle impact assessment

A variety of environmental impact connected with environmental resources consumption and emissions can make damage to human health through various midpoint indicators, including global warming,

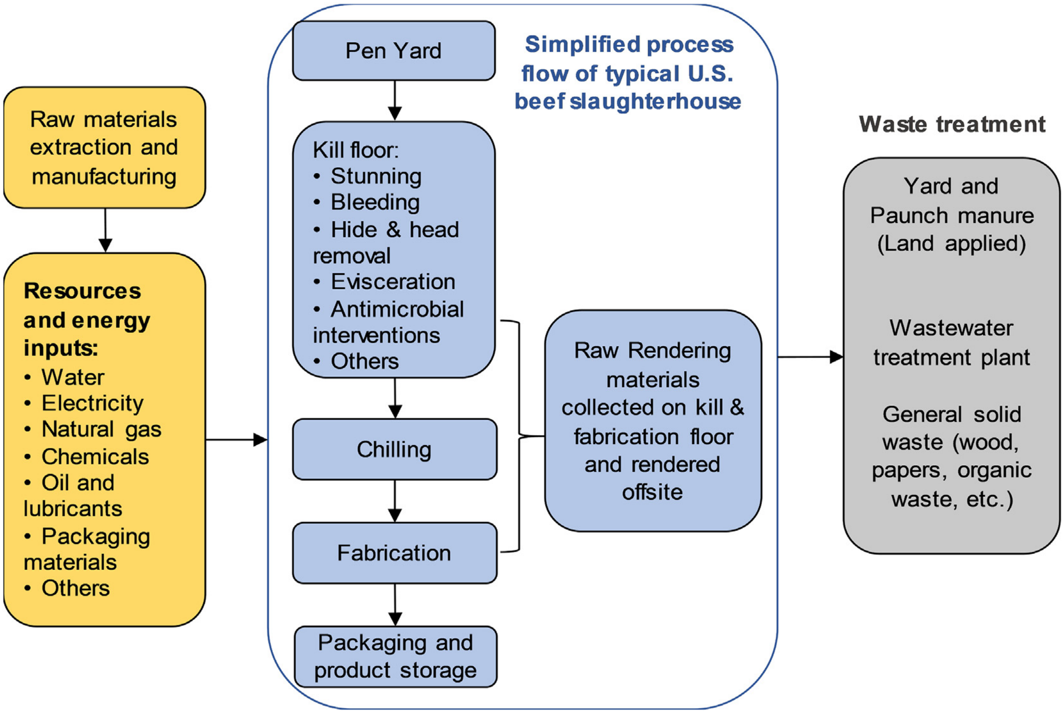

Fig. 2. System boundary of the U.S. beef slaughtering in this study.

stratospheric ozone depletion, ionizing radiation, ozone formation, particular matter formation, human toxicity (i.e., cancer and noncancer toxicity), water consumption (Huijbregts et al., 2017). These midpoint indicators exert threats to human health via various damage pathways, including respiratory disease, different types of cancers, other diseases, and malnutrition. The characterization-based methods for these environmental impacts were adopted from the ReCiPe 2016 to calculate the endpoint impact (i.e., human health) expressed in DALY (Huijbregts et al., 2017). It is recognized that the ReCiPe method developed in Europe may not be as relevant to the United States as other assessment methods, such as TRACI developed by U.S. EPA (Bare, 2012). However, the ReCiPe method converts environmental midpoint indicators to the endpoint human health impact in DALY, allowing comparisons of various sources of disease burden in the same context, which has been applied in other studies to evaluate human health tradeoffs of various systems. Internationally accepted methodologies are available for converting most midpoint indicators from ReCiPe 2016 into the endpoint on human health. However, characterization factors of human toxicity are still under development. To comprehensively quantify toxicity impacts on human health, we applied both models (ReCiPe 2016 and USEtox 2.0) for comparison (Huijbregts et al., 2017; Marian Bijster et al., 2017). The health impacts from odors and noise during beef slaughtering activities cannot be quantified using currently available assessment methods (i.e., ReCiPe 2016). However, the health impacts from odors and noise may be reflected in the occupational hazards when associated injuries are reported to the Injuries, Illnesses, and Fatalities (IIF) program.

2.3. Disease burden of occupational hazards from beef slaughtering

Occupational hazards to human health have not been incorporated into the existing life cycle impact assessment methods (e.g., TRACI v2.1 and ReCiPe 2016). Scanlon et al. (2013) developed the methodology named work environment disability-adjusted life year (WE-DALY) to estimate disease burden of occupational hazards, expressed in DALY. WE-DALY utilized data on industry-wide work-related injuries, illnesses, and fatalities reported by BLS to quantify hazards in DALY associated with worker safety from various hazards, such as physical, chemical and biological hazards. WE-DALY is composed of YLL and YLD based on industry-wide fatal and nonfatal injuries data from the U.S. Census Bureau North American Industrial Classification System (NAICS) code (US Census Bureau, 2012).

Three NAICS codes are relevant to occupational hazards in beef slaughtering and were extracted from BLS, including 1) NAICS 311611 "Animal (except poultry) slaughtering"; 2) NAICS 311612 "Meat processed from carcasses"; and 3) NAICS 56172 "Janitorial services". Specifically, NAICS 311611 and NAICS 311612 were related to production activities in beef slaughtering while NAICS 56172 was connected with cleaning and sanitation activities in beef slaughterhouses based on the number of employees. Those NAICS codes do not specifically represent the beef industry. Therefore, two methods were applied to allocate DALY of those NAICS codes. For NAICS 3116111 and 311,612, we allocated DALY to beef meat based on the fraction of the weight of beef meat to the total weight of various meats. We include NAICS 311612 to fully consider the meat processed in the slaughterhouse, although we recognize that NAICS 311612 also includes other meat processing facilities that do not slaughter. For NAICS 56172, we allocated DALY to beef industry based on the ratio of the numbers of janitorial workers in beef slaughtering plants to the total numbers of janitorial workers across all industry. The allocation methods are provided in SI Appendix, Tables S3.9 and S3.10. Details regarding the procedures and calculations YLD and YLL for the three NAICS codes are provided in Part 3 of SI Appendix, Tables S3.1 to S3.8. A summary of DALY from occupational hazards related to the U.S. beef slaughtering industry is provided in Table S3.11.

2.4. Normalization reference

The disease burden (DALY) was calculated using the same normalization reference value, as 1000 kg live-weight beef (1000 kg LW beef). We acknowledge multiple by-products are produced from beef slaughterhouse. However, the focus of beef slaughterhouse in this work is the environmental impacts associated with processing live-weight cattle, instead of byproducts produced from slaughterhouses. The carcass weight was converted to live weight equivalent for foodborne illnesses calculation (USDA ERS, 2018a) based on the average annual U.S. domestic beef consumption between 1998 and 2008 since the time period (1998–2008) is consistent with the foodborne data. The total annual cattle in live weight in the U.S. was used for normalizing environmental impacts and occupational hazards from U.S. beef slaughtering (USDA ERS, 2016). Due to exports and imports of beef, the U.S. beef slaughtering and U.S. beef consumption have two slightly different system boundaries. The amount of beef consumed and processed in the U.S. are assumed to be same due to the almost equivalent mass of U.S. beef imported and exported, both accounting about 7 to 10% of the U.S. beef market (USDA ERS, 2016).

2.5. Uncertainty estimates

For DALY estimation on foodborne illnesses, this study captured uncertainty regarding the range of the numbers of foodborne illnesses for each specific pathogen. That is minimum, most probable, and maximum numbers of foodborne illnesses extracted from original data on the literature (Painter et al., 2013). Uncertainty associated with DALY per 1000 cases for each pathogen was not presented due to insufficient data available to derive appropriate distributions. For DALY estimation on environmental impact, uncertainty underlying in background processes and on-site inventory data was estimated by a Monte Carlo Analysis (1000 runs) within SimaPro 8.4 LCA software (PRé Consultants, The Netherlands). Frequency distributions on background process were provided by their databases while frequency distributions of onsite inventory data were evaluated by Pedigree matrix built within SimaPro 8.4 (Ciroth et al., 2016). Underestimation of work-related injuries and illnesses has been a major issue in the BLS data (Leigh et al., 2004). For DALY estimation on occupational hazards, uncertainty due to undercounting issues of nonfatal injuries reported from U.S. BLS was assumed as 50% in this study, based on undercount estimates from the public literature that reported an underestimation between 33% and 69% of nonfatal injuries (Leigh et al., 2004). The uncertainty of other factors related to occupational DALY estimation (e.g., disability weight, duration time, attribution of short-term and long-term injuries) was not evaluated in this study due to data limitations.

3. Results

Fig. 3 presents the disease burden by seven primary pathogens on a general-consumer level (DALY per 1000 kg LW beef) and an infected-consumer level (DALY per 1000 cases). *Salmonella* results in the highest disease burden for the general consumer. *Escherichia coli* O157 cause a similar number of infected consumers as *Salmonella*, but the disease burden for general consumers is only around one-fifth of that from *Salmonella* due to less severe symptoms. *Listeria monocytogenes* causes the highest disease burden per case but has a lower DALY per 1000 kg LW beef due to the lower number of cases. *Clostridium perfringens* has a relatively mild burden per case but the burden for general beef consumers is ranked as a second place due to the higher frequency of cases. Norovirus, *Bacillus cereus*, and *Staphylococcus aureus* cause a lower burden for both general and infected consumer. There is significant variability of the burden on the general-consumer level from *Salmonella* and *Listeria monocytogenes* due to the uncertainty of the estimated number of cases.

As shown in Fig. 4A, global warming and fine particle matter formation were found to be the two dominant environmental categories for human health impacts, accounting 62% and 28% of total environmental DALY, respectively, as illustrated by the breakdown of total environmental DALY. Human toxicity (6%) and water consumption (4%) have fewer impacts on the overall human health while human health impacts from the other environmental pollutants (i.e., ozone formation, stratospheric ozone depletion, and ionizing radiation) are relatively minimal (0.4%). From a resource perspective, the onsite consumption of natural gas and electricity for slaughtering cattle at plants are the two major contributors, responsible for 34% and 32%, respectively. This is mainly due to their carbon dioxide and sulfur dioxide emissions, thus causing human health impacts through global warming and fine particulate matter formation. The rendering process contributes about 11% of total environmental DALY, since the rendering process is also an energy intensive process where bones, fats, meat scraps were rendered into a wide range of byproducts (e.g., edible lards, bone meal). Full process contribution can be found in SI Appendix, Table S2.5.

The human toxicity using characterization factors from USEtox 2.0 is about 5-fold higher for human toxicity than the ReCiPe 2016 method shown in Fig. 4B. Most sources result in higher human toxicity using the USEtox 2.0 method, with the sludge from wastewater treatment being the largest due to heavy metal emissions. The main heavy metals contributing to human toxicity are substances Zinc, Chromium VI and Mercury. Detailed substance contribution is provided in SI Appendix, Tables S2.6 to S2.7. The contribution to the difference between the two methods is also quantified in SI, Appendix Table S2.8 with Zinc contributing (21%), Chromium VI (23%) and Mercury (10%). Similar

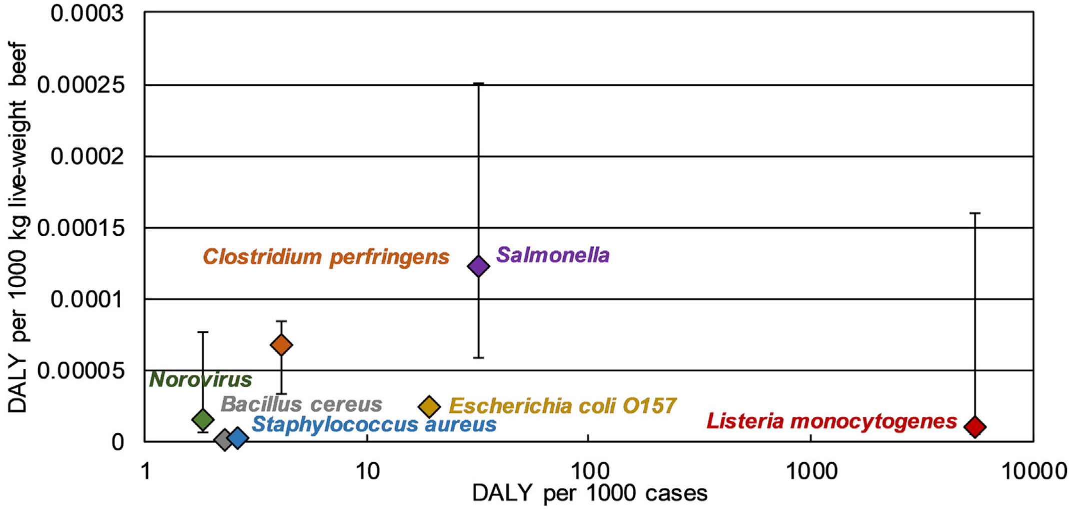

Fig. 3. Ranking of disability-adjusted life year (DALY) caused from seven primary pathogens normalized by beef weight (y-axis) and by the number of cases (x-axis) based on data from the literature on the national scale (Havelaar et al., 2012; Painter et al., 2013; Scallan et al., 2015). Tails represent minimum and maximum estimates of DALY per 1000 kg live-weight beef while markers represent most probable estimates. Note horizontal axis is on a logarithmic scale.

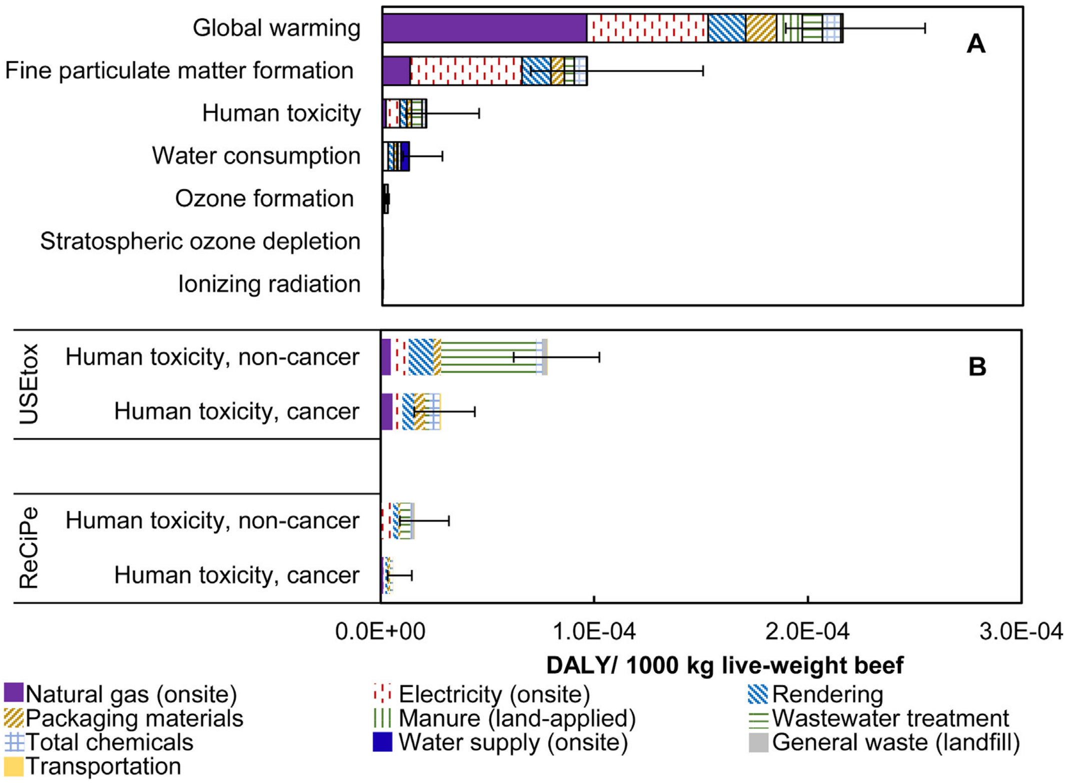

Fig. 4. Disability-adjusted life year (DALY) by various environmental midpoint categories from beef slaughtering. (A) Breakdown of environmental impacts using ReCiPe method. (B) Comparison of human toxicity result from two methods (i.e., ReCiPe 2016 and USEtox 2.0). The uncertainty bar of environmental impacts stands for lower and upper bounds at 95% confidence intervals via Monte Carlo simulation (1000 runs). Total chemicals include chemicals used during processing and cleaning, and other uses (e.g., oils and lubricants).

differences are found in other studies (Heimersson et al., 2014; Rosenbaum et al., 2008). The ReCiPe 2016 method uses a global multimedia fate, exposure, and effects model named "USES-LCA 2.0" to evaluate the cancer and non-cancer toxicity on human health (van Zelm et al., 2009) while USEtox 2.0 was developed based on several models, including USES-LCA (Rosenbaum et al., 2008). For consistency, we use human toxicity results based on ReCiPe 2016 to compare with the other two impacts in the subsequent comparison (Fig. 6). The environmental impacts at midpoint level based on ReCiPe 2016 method were also provided in Table S2.9 for reference.

Beef slaughtering not only consumes resources and produces wastes, but also causes higher injury rates than the average across U.S. private industries (Occupational Safety and Health Administration, 2017). Fig. 5 quantifies occupational hazards in DALY, allowing a comparison to environmental and foodborne human health. A large number of occupational injuries have been reported to Injuries, Illnesses, and Fatalities (IIF) program as unspecified nonfatal injuries, thus unable to be classified into the specific codes based on Occupational Injury and Illness Classification System (Bureau of Labor Statistics, 2012) (SI Appendix, Table S3.1). As illustrated in SI Appendix, Tables S3.3 and S3.6, duration assignment and the disability weights of unspecified injuries were averaged from the other specific injuries provided by IIF. It was found that unspecified nonfatal injuries have the highest occupational disease burden (39%). Multiple traumatic injuries involve traumatic disorders with equal severity is responsible for 22% of the entire occupational human health impacts, followed by amputations (14%), fatal injuries (11%), carpal tunnel syndrome (8%), and the combination of heat and chemical burns (6%).

Most DALY caused by occupational hazards is connected to life-long nonfatal injuries as shown in Fig. 5. The duration of lifelong injuries is usually two to three orders of magnitude higher than the duration of short-term injuries (SI Appendix, Table S3.5), thus lifelong injuries being a major contribution of occupational DALY. Similar findings are also found in other studies quantifying public health impact. For example, in a study evaluating drinking water on public health impacts, long-term diseases have controlling effects on human health impacts using DALY (Havelaar and Melse, 2003). Most lifelong injuries occur during processing shift of beef slaughterhouses, where a large number of workers, are engaged in activities such as slaughtering, cutting, and fabricating.

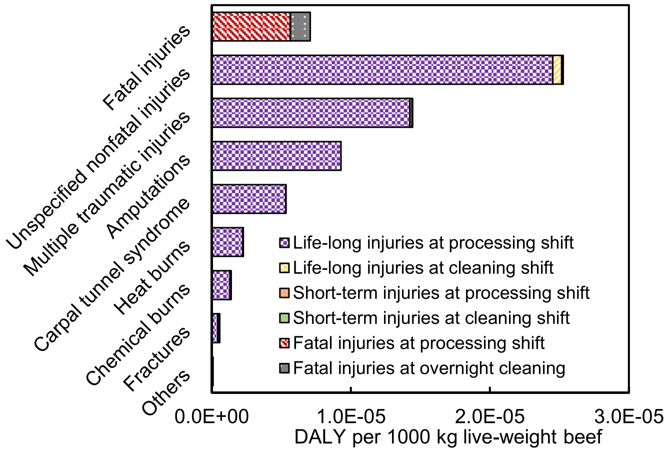

Fig. 5. Disability-adjusted life year (DALY) caused by various occupational hazards during beef slaughtering. Soreness, sprains, strains, tears, cuts, lacerations, bruises, and punctures, are combined as "Others".

Fig. 6 compares the relative human health impacts from foodborne illnesses from beef consumption, environmental impacts and occupational hazards from beef slaughtering. The foodborne illnesses are

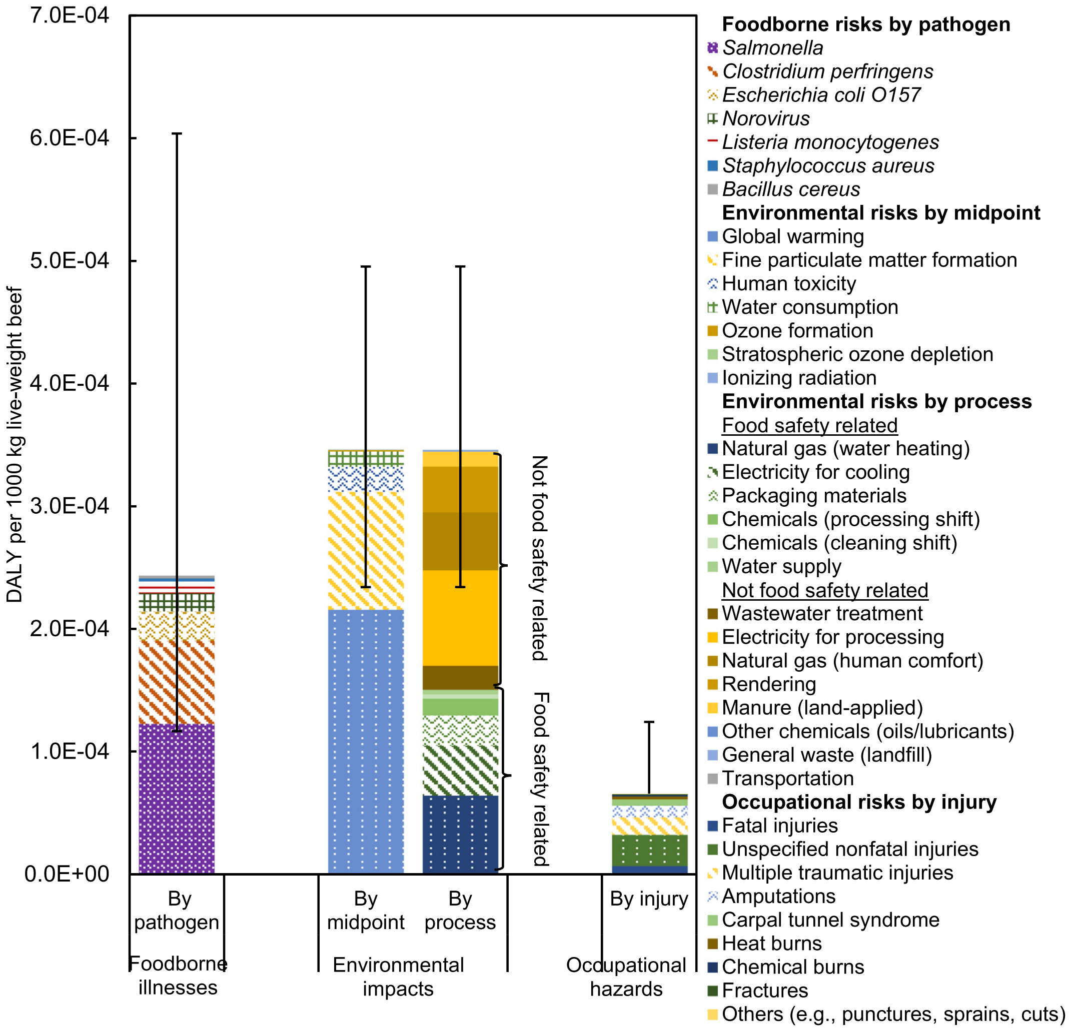

Fig. 6. Comparison of the three impacts on human health. The uncertainty bar of foodborne illnesses represents disability-adjusted life year (DALY) caused by the minimal and maximum cases of foodborne illnesses. The uncertainty bar of environmental impacts stands for lower and upper bounds at 95% confidence intervals via Monte Carlo simulation 1000 random samplings. The uncertainty bar of occupational hazards assumes 50% of unfatal injuries are not reported.

separated by pathogen. The total environmental impacts are displayed from two perspectives: 1) by midpoint (e.g., global warming, particulate matter formation) and 2) by the process to which resource uses are allocated. Occupational hazards are separated by different types of injuries. The stacked bar of environmental impacts by the process was further separated into two groups (i.e., directly relevant to food safety and indirectly relevant to food safety) to better understand the contribution of environmental impacts from various processes at the plant to the total human health impacts (Fig. 6). The following six processes as directly relevant to food safety are: 1) natural gas for water heating for sanitation; 2) electricity for cooling; 3) packaging materials; 4) chemicals (processing shift); 5) chemicals (cleaning shift); 6) onsite water use, accounting 42% of the entire environmental human health impacts. The other 58% are considered as not directly related to food safety (e.g., wastewater treatment, electricity for processing equipment, natural gas for space heating), but may be impacted by food safety changes (e.g., use of larger organic acid flow rates may increase resources required for wastewater treatment).

The foodborne illnesses are responsible for 2.4×10^{-4} DALY (minimum: 1.2×10^{-4} DALY; maximum: 6.0×10^{-4} DALY) per 1000 kg LW beef. The environmental impacts from beef slaughtering cause 3.6×10^{-4} DALY (2.3×10^{-4} to 5.0×10^{-4} DALY at 95% confidence interval) per 1000 kg LW beef. The occupational hazards connected to beef slaughtering cause 6.6×10^{-5} DALY for processing 1000 kg live weight if all injuries are reported to IIF and 1.2×10^{-4} DALY if only 50% of nonfatal injuries are reported to IIF. Quantifying disease burden from various sources involves assumptions due to inherent heterogeneity and lack of information and knowledge on specific diseases. A general conclusion could be that disease burden expressed in DALY from the three impacts is comparable to each other considering the uncertainty. DALY from occupational hazards is lower than foodborne and environmental DALY even though 50% of underreporting of nonfatal injuries was assumed.

4. Discussion

This study presents an integrated framework for evaluating human health associated with U.S. beef consumption and slaughtering. The overall goal of this work is to help decision makers target efforts on controlling and minimizing the overall human health impacts related to U.S. beef consumption and slaughtering. Such a comparable assessment enables the evidence-based discussion about policy and initiatives of the beef industry. Further examination should be performed for some relatively resource-intensive steps at slaughtering plants to optimize the overall public health DALY reductions. As environmental impacts and foodborne illnesses are negatively correlated, any improvements in food safety interventions should be compared with the sum of the two impacts for the baseline scenario. Currently available LCA methods do not include characterization factors of two important human health concerns (i.e., foodborne illness and occupational hazards). The results from this study can serve as new characterization factors for beef products in future LCA studies and method can be applied to generate human health characterization factors for other food products.

The resources used in beef slaughterhouses (e.g., electricity for cooling and packaging materials) are used for preventing beef products from being spoiled, thus reducing a significant amount of food waste and its related environmental impacts. Such an essential and beneficial function of resources have not been reflected in the DALY estimated in this study. Optimizing resource use efficiency may focus on processes not directly contributing to improving food safety but causing high environmental human health impacts, such as electricity for processing (i.e., equipment motors and lighting systems) and natural gas for space heating.

Foodborne illnesses caused by unspecified agents have not been included due to insufficient data and understanding to attribute sources to beef consumption (Scallan et al., 2011a). In this study, seven leading pathogens representing 94% of total foodborne cases due to beef consumption in the U.S. were investigated. In this respect, the contribution of foodborne DALY may increase if impacts from unspecified pathogens are considered. It is also recognized that not all beef foodborne diseases are caused by insufficient sanitation at the stage of beef slaughtering plants. It could be caused by improper cooking and cross-contamination at the consumer stage. However, a research gap still exists on how to track the sources causing beef foodborne diseases back to beef consumption or slaughtering stages. Obradovich et al. (2018) employed millions of data points from regulatory agencies to track the impacts of temperature and precipitation on daily activities of regulators (Obradovich et al., 2018). More transparent and granular data are needed for the industry and researchers to track foodborne illness data with environmental impacts and occupational hazards associated with food safety interventions during processing through the big data analysis such as the study of Obradovich et al.(Obradovich et al., 2018) or through open and distributed data system (e.g., blockchain) (Yiannas, 2018).

It has been reported that around 2×10^{-2} to 3.0×10^{-2} DALY is associated with environmental life cycle impacts for treating 10,000 m^3 of wastewater (Heimersson et al., 2014). In our study, the environmental life cycle impacts at the beef slaughtering are about 3.6×10^{-4} DALY per 1000 kg LW beef, which is comparable to human health burdens caused by treating 100 m^3 wastewater, which is slightly less than the annual wastewater per capita in the United States (USGS, 2016). The combined disease burden from the three impacts is 6.6×10^{-4} DALY per 1000 kg LW (Fig. 6), which is equivalent to about 20.1 minutes loss of healthy life based on the per capita U.S. beef consumption of 35.9 kg in carcass weight annually in 2016 (USDA ERS, 2018b).

Key strategies within the beef slaughtering to reduce environmental impacts include 1) optimizing electricity, natural gas, and chemicals within processes, 2) utilizing cleaner sources for electricity production, 3) decreasing direct emissions of carbon dioxide, sulfur dioxide, and methane from natural gas combustion via boiler, 4) reducing onsite cold and hot water consumption concurrent with burdens from wastewater treatment, and 5) developing and adopting greener packaging materials and chemicals that impose less burdens to the environment. As natural gas and electricity consumption are the two major contributors to the human health impacts by environmental pollutions, upgrading cleaner energy sources and optimizing the efficiency of energy use at the plant may offer the largest human health benefits. Environmental impacts caused by beef slaughtering may be dwarfed when comparing to that in beef pre-harvest stage (i.e., feed, cow-calf, and feedlot) due to the nature of cattle growth that produces large amount of methane as a greenhouse gas and requires intensive energy and water (Battagliese et al., 2015; Eshel et al., 2014). However, resources and pollutions from the pre-harvest stage are related to beef growth rather than beef safety and thus is excluded from this discussion.

Scanlon et al. (2015) applied the occupational approach as applied in this study and concluded 1.3×10^{-7} DALY and 2.6×10^{-7} DALY are associated with treating 1 kg of municipal solid waste by incineration and landfill, respectively. In other words, the occupational hazards from beef slaughtering (6.6×10^{-5} DALY per 1000 kg LW beef) are equivalent to occupational hazards for disposing of 254 to 508 kg of municipal solid wastes. Reduction of occupational hazards is anticipated to be largely independent of the food safety steps, since a key to the reduction may be improvements in training programs for personal protective equipment, and replacing manual-control equipment with automated equipment. Reductions of antimicrobial chemical and energy uses may also reduce the hazards of chemical and heat burns, and other concurrently traumatic disorders.

As identified in Fig. 6, 42% (1.5×10^{-4} DALY/1000 kg LW) of the entire environmental human health impacts at the plant are associated with food safety steps. For occupational hazards, injuries due to heat and chemicals burns are identified to be relevant to food safety operations, accounting about 3.6×10^{-6} DALY/1000 kg LW. These two combined impacts (i.e., environmental impacts and occupational hazards) from food safety steps at the plant is on average lower than foodborne illnesses (2.4×10^{-4} DALY). New or modified food safety interventions should be considered jointly with environmental and occupational impacts to prevent unintended shifts or increases in human health impact. Careful application of additional resources to food safety interventions may reduce foodborne DALY, with minimal increase in environmental and occupational impacts. The results from this study can serve as a baseline for evaluating incremental human health benefits from various interventions.

Like other studies on human health assessments, our work has several limitations even though based on the best data currently accessible. Data on the three impacts were obtained from the different time periods and thus human health damages might be slightly different. The environmental impacts are based on only two commercial beef slaughtering plants located in the Midwestern U.S., which might not well represent the whole U.S. beef slaughtering industry. In addition, certain specific processes (e.g., blood separation and treatment, different types of solid waste) are aggregated into more general processes (e.g., general solid waste for landfill). An exhaustive LCA is needed to enhance the standings environmental impacts on human health from specific processes. However, collecting the detailed process-level data in commercial beef facilities are challenging in many aspects, which took two years to finish the data collection. The two plants are considered as typical slaughterhouses as they apply typical processes and their overall resource uses (e.g., water, energy) are in the range of reported values in the literature (Li et al., 2018b). Therefore, we believe that gathering additional data on resource usage of additional specific processes will not change the overall conclusions of this work. Occupational hazards of beef slaughtering facilities during the construction stage were not considered in this study due to data limitations. Construction of facilities and infrastructure equipment can contribute to considerable occupational DALY compared to the operating stage (Scanlon et al., 2015).

Although there is uncertainty inherent with human health studies, the framework used in this study has broad implications for the other food processing industry. Future study should continue comparing the human health impacts from other food processing sectors (e.g., pork, poultry, dairy, egg) on the same metric (e.g., DALY per kilocalorie). This would provide information to consumers, regulators, and policy makers to simultaneously compare the overall human health burden of producing different types of protein. Such quantitative evaluations for the food processing industry can yield data-driven solutions to minimize the overall burden of human health in the food industry ultimately.

5. Conclusions

To understand the human health impacts of foodborne illnesses of beef consumption, and the environmental impacts and occupational hazards of beef slaughtering, we developed an interdisciplinary methodology to quantify the tradeoffs. The results show that the three sources of human health impact are of the same magnitude. Major contributors within each health burden source are evaluated and improvements for sustainable development of the U.S. beef industry are identified. We also propose reductions in foodborne pathogens by resource-intensive food safety interventions should be considered jointly with environmental impacts and occupational hazards to prevent unintended shifts or increases in human health impact. As consumers and the beef slaughtering industry focuses on sustainability in addition to employee and beef microbiological safety, this study has particular relevance for considering the potential for trade-offs between food safety, occupational hazards, and environmental impacts.

Declarations of interest

None.

Acknowledgments

This work was supported by National Institute of Food and Agriculture, U.S. Department of Agriculture [grant number 2012-68003-30155]. We appreciate the two commercial beef slaughtering plants who granted access and provided help to collect inventory data in their facilities. We thank Rami Ziara, Courtney Kinser, and Sam Hansen for many visits to the two plants for collecting the detailed process-level inventory data. The authors also thank the Chinese Scholarship Council for financial support for Shaobin Li's doctoral study at the University of Nebraska-Lincoln.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.05.051.

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