A comparative analysis of the greenhouse gas emissions intensity of wheat and beef in the United States

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Abstract
The US food system utilizes large quantities of liquid fuels, electricity, and chemicals yielding significant greenhouse gas (GHG) emissions that are not considered in current retail prices, especially when the contribution of biogenic emissions is considered. However, because GHG emissions might be assigned a price in prospective climate policy frameworks, it would be useful to know the extent to which those policies would increase the incremental production costs to food within the US food system. This analysis uses lifecycle assessment (LCA) to (1) estimate the magnitude of carbon dioxide equivalent (CO$_2$e) emissions from typical US food production practices, using wheat and beef as examples, and (2) quantify the cost of those emissions in the context of a GHG-pricing regime over a range of policy constructs. Wheat and beef were chosen as benchmark staples to provide a representative range of less intensive and more intensive agricultural goods, respectively. Results suggest that 1.1 ± 0.13 and 31 ± 8.1 kg of lifecycle CO$_2$e emissions are embedded in 1 kg of wheat and beef production, respectively. Consequently, the cost of lifecycle CO$_2$e emissions for wheat (i.e. cultivation, processing, transportation, storage, and end-use preparation) over an emissions price range of $10 and $85 per tonne CO$_2$e is estimated to be between $0.01 and $0.09 per kg of wheat, respectively, which would increase total wheat production costs by approximately 0.3–2% per kg. By comparison, the estimated lifecycle CO$_2$e price of beef over the same range of CO$_2$e prices is between $0.31 and $2.60 per kg of beef, representing a total production cost increase of approximately 5–40% per kg based on average 2010 food prices. This range indicates that the incremental cost to total US food production might be anywhere between $0.63–5.4 Billion per year for grain and $3.70 and $32 Billion per year for beef based on CO$_2$e emissions assuming that total production volumes stay the same.

Keywords: food, energy, lifecycle analysis, greenhouse gas policy, carbon tax

[Online supplementary data available from stacks.iop.org/ERL/9/044011/mmedia]

1. Introduction
Shifts in food production and federal food policy over the past few decades have contributed to the affordable and abundant food supply in the US. In particular the confluence of industrialized agriculture, improved agricultural science, affordable and available energy and water, and government subsidies, has come with significantly improved productivity per acre and per farmer. It also has attendant negative externalities, such as greenhouse gas (GHG) emissions, that are not included in retail food prices. Although consensus has not been reached regarding the most efficient mechanism to curb anthropogenic GHG emissions, rising concern over the consequences of global...
climate change and shifts in public and political sentiment suggest that emissions regulatory pricing structures might be implemented in the US in the future. Because the US food system is energy and GHG intensive, these new structures will have non-trivial impacts on production costs. However, an up-to-date assessment of the full lifecycle GHG emissions and quantification of the potential for higher costs for the US food system has not been conducted to the authors’ knowledge. Because these costs are non-obvious to estimate, this work seeks to develop and illustrate a methodology for quantifying the energy, emissions, and costs for the US food system in the context of a price on GHG emissions. The methodology illustrated normalizes data for energy, food prices, food productivity, and emissions for the year 2010. Wheat and beef, representing the typical range of energy and GHG emissions intensities, are used to illustrate the range of potential impacts of GHG emissions prices.

2. Background

Lifecycle assessment (LCA) is a systematic tool to quantify the impacts of a product or process over its entire lifespan including raw resource extraction or cultivation, transportation, manufacturing, storage, use, maintenance, and ultimate disposal (i.e. ‘cradle to grave’) [1, 2]. Here LCA is used to quantify the lifecycle GHG emissions associated with wheat and beef on a per unit mass basis. Carbon dioxide equivalent (CO₂e), the international standard metric for measuring and reporting GHGs, is used to normalize the global warming potentials of different GHGs so that they can be readily compared [3–6]. (This metric is also the standard that the EPA uses for its GHG budget documents, and is therefore relevant in the context of current US energy policy [5, 6].) These GHGs include Carbon Dioxide (CO₂), Methane (CH₄), Nitrous oxide (N₂O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulfur hexafluoride (SF₆) [3–5]. The CO₂e metric weights each GHG according to its global warming potential (GWP). For example, CH₄ and N₂O have significantly larger GWP than CO₂, 25 and 298 times CO₂, respectively, when considered over a 100 year time horizon [7].

LCA has been a common tool for quantifying the environmental impacts of various aspects of food production in the literature. Several methodologies have been utilized such as including economic input–output LCA [8, 9], consequential LCA [10, 11], and attributional LCA [2, 11–18]. Much of the research to date has been limited to analyzing specific food products [12, 13, 16], agricultural production systems [16, 19–23], or industrial processes [12], due to challenges in characterizing spatial and temporal variabilities, as well as limited data availability at the systems scale [12, 14]. National greenhouse gas assessments for US food production across agricultural, manufacturing, retail, and food preparation stages have not been published.

The CO₂e emissions resulting from food production are a combination of GHGs (primarily CO₂) derived from fossil-fuel combustion, as well as non-combustion (primarily CH₄ and N₂O) emission sources. Although the GHG emissions associated with upstream food production in the US have not been quantified in a systematic way, the literature suggests that the US dedicates between 10.5% and 19% of its annual energy consumption to produce food [18, 24, 25]. This energy use correlates to approximately 10–19 quadrillion British Thermal Units (BTU) of 2010 energy use [26]. While many environmental analysts criticize the large quantities of fossil-fuel inputs associated with modern industrialized farm practices, those energy inputs have enabled significant improvements in productivity since World War II [27]. Furthermore, when accounting for GWP, the emissions associated with fossil-fuel inputs at the farm are actually far less than the emissions associated with agricultural CH₄ and N₂O production [6]. Because these non-CO₂ emissions are emitted from processes other than direct energy consumption, the GHG emissions resulting from food production do not scale linearly with the lifecycle energy consumed for each respective type of food.

While it is generally accepted that raising livestock for meat production has significant GHG emissions that are not incurred with plant-based food production [14, 19, 25, 28–35], LCA is hindered by the lack of robust energy and GHG data across complex supply chains and variability across farm systems, manufacturing processes, and food preparation [12, 14, 36]. Farm emissions are particularly difficult to quantify since agricultural entities vary considerably in fertilizer application, organic versus conventional farming practices, tilling practices, feeding patterns, animal and waste management, and fuel inputs [2, 16, 19, 21, 22, 31, 33, 36, 37].

Overall, the agricultural sector contributed nearly 7% of total US GHG emissions in 2010 [6]. The CO₂e emissions from energy consumption in the agricultural sector or the processing of chemical inputs are not included in this total. These emissions are included in the energy sector category of national emissions accounting reports. Agricultural soil management alone represented 53% of that total, releasing 245 teragrams (Tg) CO₂e of the 462 Tg CO₂e that were emitted in the agricultural sector in 2010 [6]. Soil emissions are due to large quantities of N₂O that are produced through the microbial processes of nitrification and denitrification [4, 6]. The rearing of animals on farms produced an additional 209 Tg of CO₂e through enteric fermentation and the production of waste [6]. Rice Cultivation represented the small remaining fraction of emissions in the agricultural sector [6].

Enteric fermentation occurs through the release of CH₄ during exhalation or belching of animals due to the microbial fermentation that occurs during digestion [32]. This process is especially pervasive in ruminants, such as cattle, goats, and sheep, and contributed 24% of total US CH₄ emissions in 2010, making it the second largest source of CH₄ in the nation after natural gas systems. Livestock waste contributed 9% of total US CH₄ and 5% of total N₂O emissions, respectively, in 2010 [6]. CH₄ is emitted through the process of anaerobic digestion of manure, while N₂O is emitted through the nitrification and denitrification of organic nitrogen in livestock waste and urine [4].

Although the scientific literature points to reduced meat consumption as an effective mitigation strategy in regards to climate change [25, 30, 31, 38, 39], to date, agricultural production has been largely ignored in climate policy
[40, 41]. A study by Wiresenius, Hedenus, and Mohlin concludes that implementing an emissions tax of €60 per tonne CO$_2$e ($77 per tonne CO$_2$e in 2012 USD) on animal food products would reduce agricultural CO$_2$e emissions in the EU by 32 million metric tons annually, which represents approximately 7% of the EU’s total, annual agricultural GHG emissions [40]. An emissions price on the downstream consumption of GHG-intensive agricultural goods (i.e. a GHG emission tax or emissions trading scheme) is one means of implementing a CO$_2$e construct using price signals and market forces to implement diet shifts as a climate mitigation strategy.

The US has not historically imposed a price on GHG emissions, but recent actions by the federal government point to the possibility of more stringent emissions legislation in the future. In 2013, the US EPA proposed a new carbon pollution standard for new power plants to be implemented thorough the Clean Air Act (CAA) [42]. However, active pollution regulations through the US CAA, Cross State Air Pollution Rules, and National Ambiance Air Quality Standards do not include provisions for agricultural emitters [43, 44]. Furthermore, the agricultural sector is currently exempt from carbon trading schemes in other countries. Nonetheless, in the event that agricultural operations are incorporated into the policy regimes regulating GHG emissions in the future, it would be useful to know what the incremental (i.e., increased) cost to food production might be as there might be subsequent impacts on retail food prices. However, those emissions-based costs for food production have not been rigorously quantified to date in the US. This paper seeks to fill that knowledge gap. To do so, the marginal cost of producing 1 kg of wheat and 1 kg of beef is calculated by quantifying the lifecycle CO$_2$e emissions (direct and indirect) associated with each food category in 2010 (over each stage of production) and applying a GHG emissions price. Wheat and beef were chosen as benchmark staples to provide a representative range of less intensive and more intensive agricultural goods, respectively. The study evaluates a GHG emissions tax over a range of prices suggested in the literature [45–48]. This paper extends and improves upon the prior work done by the authors [49] by updating and normalizing pertinent data sets (i.e. greenhouse gas inventories, energy consumption data, food production data, commodity prices, etc) to a common reference year. The analysis is based on US food production in the year 2010 and does not consider food imports from other countries.

Although this analysis is a starting point in accounting for the environmental externalities associated with the production, transportation, manufacturing, and handling of food, it does not include the cost of other externalities such as water pollution from agricultural runoff, soil erosion, or land-use changes. Additionally, it does not assess the societal costs and benefits associated with food production, such as nutrition, obesity, rural economic development, and food security.

3. Methodology and results

This analysis (1) estimates the CO$_2$e lifecycle emissions associated with producing wheat and beef in the US and (2) estimates the incremental cost on production for a range of emissions prices.

To organize energy and emissions data throughout the analysis, a series of indices were employed in which subscript $i$ refers to fuel type, $j$ refers to food category ($j = 1$ for wheat, $j = 2$ for beef), and $k$ refers to the lifecycle production stage. This approach could be expanded to include additional food types. We consider CO$_2$e emissions over 7 lifecycle stages including agricultural production ($k = 1$), food manufacturing ($k = 2$), food packaging ($k = 3$), food service facilities ($k = 4$), food sales facilities ($k = 5$), residential food preparation ($k = 6$), and lifecycle transportation ($k = 7$). The energy consumption at each respective lifecycle stage is based on sources in the literature [18, 24, 25, 29, 50–53] and adjusted to 2010 energy use based on energy data reported by the Energy Information Administration (EIA) [26]. (Full details regarding the assumptions and adjustments made to normalize data to the 2010 reference year are provided in the supporting information (SI) available at stacks.iop.org/ERL/9/044011/mmedia document.)

US energy data, provided by the EIA, provide details about energy consumption in terms of sector, quantity, and fuel type. Thus, to quantify the GHG emissions associated with the production of a particular category of food, several transformations were necessary to convert energy data by fuel type and production stage to CO$_2$e emissions data by food category and production stage. Accordingly, several conversions were utilized to convert the energy consumed by fuel, $i$, at lifecycle stage, $k$ ($e_{i,k}$, in BTU), to the CO$_2$e emissions associated with the production of food category, $j$, at lifecycle stage, $k$ ($E_{j,k}$ in kg CO$_2$e) adapting the method laid out by Cuellar and Webber [29].

Equation (1) is used to compute $E_k$ (kg CO$_2$e), which represents the sum of GHG emissions across each pertinent lifecycle stage, $k$. $E_k$ is defined as:

$$E_k = \sum_{i=1}^{10} (e_{i,k} \times \varepsilon_i)$$  \hspace{1cm} (1)$$

where $\varepsilon_i$ is the emissions intensity factor (EIF) in kg CO$_2$e per million British Thermal Units (MMBTU) for fuel, $i$. (EIF definitions provided in SI available at stacks.iop.org/ERL/9/044011/mmedia.)

Equation (1) yields no information regarding the breakdown of emissions on a food type basis, so equation (2) is used to convert $E_k$ into value $E_{j,k}$, representing the total GHGs emitted from the production of food type, $j$, across each lifecycle stage, $k$.

$$E_{j,k} = E_k \times p_{j,k}$$ \hspace{1cm} (2)$$

where, $p_{j,k}$, is a scaling factor defined at each lifecycle stage. This variable represents the proportion of energy dedicated to food type, $j$, in respect to the total energy consumed at lifecycle stage, $k$.

Next, a unit emission intensity metric, $\beta_{j,k}$ (kg CO$_2$e kg$^{-1}$), is derived to quantify the CO$_2$e emissions (kg CO$_2$e) embedded in one kilogram of food category, $j$. (EIF definitions provided in SI available at stacks.iop.org/ERL/9/044011/mmedia.)
for lifecycle stage, \(k\). The functional unit of 1 kg (defined in terms of production mass) of each respective food category (i.e. wheat or beef) is used to normalize results so that they are comparable. In 2010, the US produced 60 and 12 billion kg of wheat and beef, respectively. Equation (3), referred to throughout this analysis, is used to quantify, \(\beta_{j,k}\):

\[
\beta_{j,k} = \frac{E_{j,k}}{m_j}
\]

where \(m_j\) (kg) is total 2010 US production by mass of food category, \(j\). Since these masses refer to the production mass, equation (3) will yield a conservative estimate of unit emission intensity since there are losses through processing, transportation, storage, and retail. The mass of beef refers to post-slaughtering weight, but still includes the mass of the bones. (The contribution of food imports to the US is not considered in this analysis.) Finally, the unit emission intensity metrics for each food category are summed across all lifecycle stages to derive one unit intensity metric (\(\beta_j\)) for wheat and beef production, respectively, in equation (4).

\[
\beta_j = \sum_{k=1}^{7} \beta_{j,k}.
\]

The purpose on this analysis was to derive an estimate of national CO\(_2\) emissions associated with plant-based and meat-based food for average US production practices. Because of the considerable scope of this task, we lean on estimates from the literature for each lifecycle stage, \(k\), to aggregate and normalize data for each production step in the year 2010. Full details regarding our assumptions and data sources utilized for each production step are provided in the SI document (available at stacks.iop.org/ERL/9/044011/mmedia).

Using these assumptions and this method, we estimate that total US wheat and beef production emitted 63 ± 7.5 and 370 ± 97 billion kg CO\(_2\), respectively, in 2010. Furthermore, it can be estimated from these conversions that the lifecycle CO\(_2\) emissions embedded in 1 kg of wheat and beef were 1.1 ± 0.13 and 31 ± 8.1 CO\(_2\) per kg, respectively (table 1), suggesting that beef is 28 times more emissions-intensive per kg of food. (Americans consume relatively less beef than wheat, so the total annual CO\(_2\) emissions from beef were only approximately 6 times larger.) These GHG estimates would be larger for wheat and beef if indirect land-use changes for food production (i.e. land-use changes that effectively reduce the capacity of biota to uptake carbon, as well any emissions resulting from the burning of biomass for deforestation) were considered [31]. Total uncertainty, \(U_{tot}\), was calculated \(U_{tot} = \left(\sum u_{jk}^2\right)^{0.5}\) where \(u_{jk}\) is the uncertainty for each of \(E_{j,k}\) and \(\beta_{j,k}\). More details regarding the assumptions made for uncertainty at every lifecycle stage are included in the Discussion section.

According to the US Bureau of Labor Statistics, 1 kg of wheat bread in 2010 cost US consumers an average of $4.00 in US cities; one kg of ground beef cost $6.30 [54]. Thus, in terms of cost, beef costs approximately 1.5 times more than wheat bread, despite emitting nearly 28 times the CO\(_2\) emissions and 30 times more energy [29] per mass produced. This disconnect between consumer cost and environmental cost indicates a market distortion that proponents of a GHG tax assert can be resolved if a price is placed on emissions. A variety of studies have identified an appropriate range of CO\(_2\) prices to be $10 to $85/tonne, so we use this range for the purposes of this analysis [45–48]. Equation (5) was used to calculate the GHG emission cost, \(CC_j\), per kg of food category, \(j\), due to CO\(_2\) emissions at a cost, \(\$\) per tonne CO\(_2\):

\[
CC_j = \frac{C_{CO2e}}{1000} \times \beta_j.
\]

The resulting ranges of CO\(_2\) costs were between $0.011 and $0.094 per kg for wheat production and between $0.31 and $2.60 per kg for beef production based on the LCA completed in this analysis. The increases in total grain production costs from CO\(_2\) emissions pricing would be on the order of 0.28–2.3% of retail prices if lifecycle CO\(_2\) emissions were priced, while the CO\(_2\) costs for beef production could be 4.9–42% of 2010 prices. It is important to note that these GHG emission costs might or might not affect retail food

| Lifecycle stage, \(k\) | \(2010\) unit emission intensity, \(\beta_{j=1,k}\) (CO\(_2\)e kg\(^{-1}\)) | Total 2010 emissions \(E_{j=1,k}\) (billion kg CO\(_2\)) | \(2010\) unit emission intensity, \(\beta_{j=2,k}\) (CO\(_2\)e kg\(^{-1}\)) | Total 2010 emissions \(E_{j=2,k}\) (billion kg CO\(_2\)) |
|-----------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Agriculture production, 1 | 0.30 ± 0.09 | 18 ± 5.4 | 27 ± 8.1 | 320 ± 97 |
| Food manufacturing, 2 | 0.22 ± 0.066 | 13 ± 3.9 | 0.22 ± 0.066 | 2.7 ± 0.81 |
| Food packaging, 3 | 0.17 ± 0.051 | 10 ± 3.0 | 0.17 ± 0.051 | 2.0 ± 0.60 |
| Food service facilities, 4 | 0.054 ± 0.011 | 3.2 ± 0.64 | 0.42 ± 0.084 | 5.0 ± 1.0 |
| Food retail facilities, 5 | 0.044 ± 0.0088 | 2.6 ± 0.52 | 0.34 ± 0.068 | 4.1 ± 0.82 |
| Residential food preparation, 6 | 0.23 ± 0.023 | 14 ± 1.4 | 1.74 ± 0.17 | 21 ± 2.1 |
| Transportation, 7 | 0.043 ± 0.013 | 2.6 ± 0.78 | 0.93 ± 0.28 | 11 ± 3.3 |
| Total (\(\beta_j\) and \(E_j\)) | 1.1 ± 0.13 | 63 ± 7.5 | 31 ± 8.1 | 370 ± 97 |
prices. While it is possible that emissions costs might drive up retail food prices, it is also possible that food prices would stay the same and profit margins for producers or retailers might get squeezed. Furthermore, it is possible that the GHG emissions prices would trigger investments in supply chain efficiencies that keep retail prices and profit margins at the same levels. Determining the likelihood of those possible outcomes is beyond the scope of this analysis.

Equation (6) was used to calculate the total net cost, TC\(_j\), of producing food category, \(j\), under a regulatory regime that induces a cost on emissions, \(C_{\text{CO}_2}\):

\[
TC_j = \frac{C_{\text{CO}_2}}{1000} \times E_j. \tag{6}
\]

In 2010 the US produced 12 billion kg of beef. Thus, the total annual cost of producing beef, assuming a relatively conservative emissions price of $10/tonne\(^{-1}\) CO\(_2\), would amount to $3.7 billion a year. By comparison, instituting a more aggressive tax (i.e. $85 per tonne CO\(_2\)) as recommended by the 2007 Stern Review [46], would induce a cost of $32 billion a year for producing beef. (By comparison, the net cost of pricing CO\(_2\) for annual wheat production would be between $0.63 and $5.4 billion a year if CO\(_2\) was priced over the same range.) If the emissions associated with the agricultural production stage (i.e. CH\(_4\) and NO\(_2\) from waste management, enteric fermentation, and soil management) were omitted from the analysis, the projected marginal cost of producing beef would only be 0.5–4.3 billion per year, nearly 90% less than the projected cost with these externalities included.

The results, summarized in table 2 and figure 1, assume that the change in the production cost of food due to the implementation of CO\(_2\) pricing would induce a linear change in retail costs to the consumer. However, as noted earlier in this manuscript, it is possible that retail costs might not change in such fashion. Furthermore, increased food cost might also lead to lower consumption, which would also cause a non-linear response in retail costs and production over time.

### 4. Discussion

This analysis, as with many LCA studies, was limited by the lack of available data regarding CO\(_2\) emissions at the various lifecycle stages. Therefore, many assumptions were made to resolve these data gaps, each of which potentially introduced error. However, these results strongly corroborate prior analyses that beef production contributes significantly more emissions than wheat production, most notably at the agricultural production stage through the biogenic emissions, N\(_2\)O and CH\(_4\) (i.e., through enteric fermentation and manure management). These results also confirm that the emissions caused by the production of food in the US food system are highly variable due to differences across lifecycle stages, especially at the agricultural production stage through variability in farm regimes, fertilizer application rates, feeding practices, soil biology, climate, and waste management practices. Emissions at each stage can also be influenced by such factors as fuel inputs, differences in technology, processing intensities, facility efficiency, and modes of distribution.

Due to the complexity of analyzing whole farm systems, the analysis in this manuscript cites data from the literature to estimate the unit emission intensity metrics for wheat and beef agricultural production [2, 17, 19, 28]. The emissions associated with the agricultural production of wheat and beef were estimated based on studies in the literature that had already normalized wheat and beef production according to the kg of CO\(_2\) emitted per kg food product produced at the farm. The unit intensity value for wheat was averaged based on two studies in the literature that analyzed emissions across a wide range of fertilizer application rates; however, these studies do not comment on error [19, 28]. For this work, an error estimate of 30% was assigned as a conservatively high benchmark since the specific scope and assumptions of each of these analyses are slightly different, and they arrive at results ranging from 0.14–0.38 CO\(_2\) per kg of wheat produced on the farm. We also assign high error to account for the large variability in farming (and animal rearing) operations. In general, the literature suggests that the emissions intensity of producing wheat on a particular farm is most sensitive to the rate and magnitude of fertilizer input, especially in terms of N\(_2\)O emissions, the most pervasive GHG in plant-based agricultural production [2, 17]. Other factors such as till or no-till practices also have large impacts on agricultural emissions [37].

The value for beef production at the farm or feedlot was based on an average of 15 conventional beef farming systems and 5 organic beef farming systems weighted according to conventional and organic beef production in the US [19, 28]. We calculated an average emission intensity values for

| CO\(_2\) price (USD/kg CO\(_2\)) | Marginal cost of CO\(_2\) per unit of wheat (USD/kg CO\(_2\)) | Total US wheat CO\(_2\) emissions (billion kg CO\(_2\)) | Marginal cost relative to average retail price (%) | Grain | Beef |
|--------------------------------|------------------------------------------------|---------------------------------------------------|-------------------------------------------------|-------|------|
| 0.01                           | 0.011                                          | 63                                                | 0.63                                            | 0.28  | 0.31 |
| 0.085                          | 0.094                                          | 63                                                | 5.4                                            | 2.3   | 2.60 |
|                                |                                                |                                                   |                                                 |       |      |

**Table 2.** Implementing a CO\(_2\) price across the lifecycle emissions of grain and beef products might increase food prices by 0.28–2.3% and 4.9–42% for grain and beef products, respectively, for the range of CO\(_2\) prices evaluated.
The incremental or marginal costs incurred by CO$_2$e emissions within a GHG-pricing regime ranged from $0.01 and $0.09 per kg for wheat production and between $0.31 and $2.60 per kg for beef production over the range of CO$_2$e prices analyzed (left). The total cost incurred to produce 60 and 12 billion kg of wheat and beef, respectively, ranged from 0.63 and 5.4 billion USD and 3.7 to 32 billion USD (right).

beef cultivation based on a weighted value of these averages, assuming that 98% of current beef production is derived from conventional systems based on the literature. Although the weighted average was 27 CO$_2$e kg$^{-1}$ of beef produced on the farm, the standard deviation of the 20 samples was 12 CO$_2$e kg$^{-1}$, indicating a large spread in estimates across the literature [19, 28]. The emission intensity of meat production varies significantly according to such factors as feed, feed production, feeding patterns (such as length and frequency), animal housing, and manure storage [12]. Since this particular stage is 1–2 orders of magnitude larger than other lifecycle stages of beef production, results are particularly sensitive to this estimate.

Data in the literature regarding the energy consumed for food manufacturing [24, 29, 52] ($k = 2$) and packaging [18, 25, 29, 53] ($k = 3$) considered different reference years and with the exception of Cuellar and Webber [29], offered no estimation of uncertainty. Furthermore, the fuel distribution of the manufacturing sector was based on a 2002 reference case detailed in a report prepared for the EPA [52]. Even after adjusting these data for this study’s reference year (2010), the ratio between the highest and lowest energy-use estimates across the various studies was nearly 2:1. In the case of food packaging, the fuel distribution had to be estimated using manufacturing data from the EIA for similar industries to calculate the emissions associated with the sector (see SI available at stacks.iop.org/ERL/9/044011/mmedia for details). We assign 30% uncertainty to these estimates as a conservative estimate.

Energy information regarding food handling was derived from EIA data. Our estimates for the energy consumed for food service ($k = 4$) and food sales ($k = 5$) facilities in reference year 2010 are based on trends in 2003 data, which may not adequately characterize 2010 energy use and fuel distribution. Since the 2003 and 2010 EIA consumption data are similar in terms of collection and reporting, it is likely that the margin of error is less than in previous lifecycle stages that consider a number of varying sources in the literature. We assign uncertainty values of 20% to these stages for both food types. The energy consumed for residential food preparation and cooking ($k = 6$) is based on DOE's 2010 Residential Energy Consumption data [55]. We assign an uncertainty value of 10% to account for any error in our energy intensity assumption for either food group. Less error was attributed here since energy data and the fuel distribution were available for the reference year, 2010.

Transportation emissions data were derived from the 1997 US Commodity Flow Survey [50], which characterizes food transport by food category and lifecycle stage. However, these data did not entirely correlate with the definitions in this analysis. For example, the US Commodity Flow Survey categories generally track the transportation of 'red meat' (which can include lamb among others), but we assume all the red meat categories are representative to the transportation of beef. Likewise, the survey characterizes the movement of value added products made with wheat ingredients (i.e. pasta, pastries, bread, etc), so we weighted these post-manufacturing transportation stages to account for the fact that these products include other food categories. We also normalized emissions by comparing aggregated 1997 transportation energy data to 2010 transportation energy data to calculate an emissions estimate for the reference year 2010. Since these data do not break out commercial transportation energy use from personal vehicle use, any gains in commercial vehicle efficiency between the years 1997–2010 might not be evident. Due to the uncertainty regarding the assumptions of lifecycle transportation emissions, we assign uncertainty values of 30% to the metrics calculated at this lifecycle stage.
In general, the US energy mix has been decarbonizing due to substantial decreases in coal-fired electricity generation and increases in the use of natural gas and renewable energy sources [56, 57]. Additionally, total energy use through 2011 has remained below 2007 levels primarily due to the global recession and tighter efficiency standards, especially in the transportation and power sectors [56, 58]. Consequently, the emissions from the electric power sector have declined since 2010 and are likely to continue to decline as it continues to decarbonize [57]. Despite this trend, the emissions due to CH₄ and NO₂ in the agricultural production stage are nearly 9 times greater than those derived from fossil-fuel consumption over the lifecycle of beef production. Thus, the decarbonization of the energy sector will not markedly reduce the emissions associated with beef production.

It should be noted that the issue of food wasted or lost throughout the supply chains is not addressed, as the CO₂e emissions at each lifecycle stage are normalized by total 2010 US wheat and beef production, respectively. Cuellar and Webber estimate that nearly 30% (in terms of mass) of the edible food supply is wasted at some point along the food chain (approximately 32% and 16% of all wheat and beef products, respectively). However, detailed data regarding how much of each food type is wasted along the supply chain are not available and therefore outside the scope of this analysis [29].

If we were to characterize food loss at each lifecycle stage, the unit emission intensity metric, \( \beta_{j,k} \), would increase as food waste increased, since the total emissions, \( E_{j,k} \), would remain the same, but the mass of unwasted food in category \( j \) would be smaller.

5. Conclusion

This analysis concludes that annual lifecycle CO₂e emissions for wheat and beef production in the US were 63 ± 7.5 and 370 ± 97 billion kg CO₂e, respectively in 2010. This analysis builds on work published in the literature, by quantifying the emissions for these two food categories across their entire lifecycle, based on total US production, using updated data and with resolution across each stage in the supply chain. These results indicate that approximately 5% of total US CO₂e emissions are caused by beef production alone. Nearly 90% of the emissions released through beef production occur at the agricultural production stage, primarily through the CH₄ and N₂O released through enteric fermentation and animal waste. Wheat production, by comparison, is associated with less than 1% of annual US CO₂e emissions, despite the fact that the US produces 5 times more wheat by mass than beef. Of any production stage associated with wheat, N₂O emissions at the agricultural stage were most significant. Consequently, implementing a price for CO₂ emissions could markedly increase the cost of producing food products that have high emissions intensity.

This analysis points to the importance of including agricultural emitters in GHG emission reduction policies if large decreases in the GHG emissions resulting from food production are to be achieved through this policy construct. Nonetheless, if agricultural entities are incorporated into future GHG policy regimes, the potential economic consequences might be significant depending on the price placed on emissions and how industrial practices and consumer behaviors respond to those price signals.

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