Cities’ Role in Mitigating US Food System Greenhouse Gas Emissions

Supporting Information

Eugene A. Mohareb*,†, Martin C. Heller, Peter M. Guthrie

1Centre for Sustainable Development, Department of Engineering, University of Cambridge, Cambridge, UK CB2 1PZ;

†Construction Management & Engineering, School of the Built Environment, University of Reading, Reading, UK RG6 6DF

2Centre for Sustainable Systems, School of Environment & Sustainability, University of Michigan, Ann Arbor, MI, USA 48109-1041

* Chancellor’s Building, School of the Built Environment, University of Reading, Reading UK, RG6 6DF, e.mohareb@reading.ac.uk;
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**S1 Explanation of Emissions Quantified in US Food System**

Below are summaries of the quantification methods for emissions from various data sources, based on the components listed within Figure S.1. As mentioned, this study applies a combination of a meta-review of LCA studies and emissions calculated based on government and literature data on energy consumption and fugitive gases (refrigerants, landfill gas, anaerobic digesters, composting).

A life cycle-based approach to estimating the greenhouse gas (GHG) emissions associated with the food system is quantified using the boundaries illustrated in Figure S.1. These include emissions from raw materials and farm-level production, as well as primary processing (i.e., milling grain to flour, canning of produce, milk pasteurization) quantified through a meta-review of life cycle assessment studies. Further processing, distribution, retailing, food service and household emissions associated with refrigeration and energy consumption is obtained using US government data. In addition, transportation data for distribution between further processing to households is also tabulated, with the exception of trips for food service sector meals. Transportation emissions related to disposal of food waste and packaging are calculated using the emissions factors from the USEPA WaRM model.

![Figure S1: Process diagram of food system life cycle stages quantified in this analysis](image)

Data related to GHG emissions have been gather from a number of sources, which are then compiled to calculate the emissions total for the US food system. Life cycle emissions from farm to primary...
processing are obtained for 99 commodities from Heller & Keoleian\textsuperscript{2} based on a literature meta-review of emissions factors of various food types and the USDA's Loss-Adjusted Food Availability dataset \textsuperscript{3}.

**S1.1 Meta-Review of LCA Studies**

The meta-review approach taken here uses published LCA data to arrive at representative carbon footprint values for the diversity of food commodities consumed in the US. Results are drawn from a variety of sources (as described in Heller & Keoleian\textsuperscript{2}), compiled by food type, and averaged across comparable commodity type. U.S.-based data is limited, and thus this meta-review includes data from other developed countries. These sources include studies representing a variety of countries of origin, climatic conditions, transportation distances, and production methods and therefore are intended to provide a reasonable range of expected values rather than a definitive result for each food type. As explained in the main manuscript, implications for potential double-counting are mitigated through the additional scrutiny of studies that may include post-primary processing GHG emissions for commodities that either have a substantial contribution to total food system emissions or substantial variation across studies. A full list of commodities and associated emissions factors is provided in the supporting information for Heller and Keoleian\textsuperscript{2} and is replicated below in Table S1. The revised list of emissions factors for modified commodities are given in Table S2.

All emissions associated with further processing, packaging, transportation, distribution, retail, household preparation, and waste disposal were calculated separately (see Figure S1). Estimates of energy demand, packaging material consumption, waste disposal are made for the year 2010 for each stage of the food supply system. These are described below.

The meta-review from Heller and Keoleian\textsuperscript{2} was refined for the top commodity contributors (defined as those that contributed more than 50 kg CO\textsubscript{2}e/cap) or those that had a substantial variation across studies (defined as greater than 100 kg CO\textsubscript{2}e/cap), presented in Table S2.\textsuperscript{2} This was to ensure that error introduced from double counting was reduced for these. The commodities included in this refinement were beef, chicken, pork, cheese, fluid milk, eggs and added sugars and sweeteners. For these foods, a further review of LCA emission factors was conducted, with assurance that boundary conditions only extend to the primary processing stage. Added sugars and sweeteners is represented by a consumption-weighted average of honey, white sugar, and high fructose corn syrup. Emissions are calculated by multiplying emissions factors by per capita demand in 2010 for each stage as presented in the loss-adjusted food availability data presented in Table S3.

Table S1: List of original commodity values, reprinted with permission from Heller and Keoleian (2015). Copyright 2015 John Wiley and Sons.

| Greenhouse Gas Emissions (kg CO\textsubscript{2} e/kg) | Number of studies in average, or proxy\textsuperscript{1} |
|------------------------------------------------------|---------------------------------------------------------|
|                                                      | Avg   | min   | max   |                     |
| **Grain products**                                    |       |       |       |                     |
| total wheat flours                                   | 0.58  | 0.29  | 0.83  | 4                   |
| rice                                                 | 1.14  | 0.78  | 1.30  | 4                   |

\textsuperscript{1} proxy: number of studies in average or individual studies for each commodity type.
| Ingredient            | 1  | 2  | 3  | 4  | 5  | 6  |
|-----------------------|----|----|----|----|----|----|
| rye flour             | 0.36 | 0.36 | 0.36 |    | 1  |    |
| corn products         | 0.66 | 0.58 | 0.73 |    | 3  |    |
| barley products       | 0.60 | 0.43 | 0.76 |    | 2  |    |
| oat products          | 0.47 | 0.47 | 0.47 |    | 1  |    |
| Fresh fruit           |    |    |    |    |    |    |
| citrus                | 0.50 | 0.25 | 1.07 |    | 5  |    |
| apples                | 0.36 | 0.26 | 0.45 |    |    |    |
| apricots              | 1.27 | 0.65 | 1.56 |    | 1  |    |
| avocados              | 1.32 | 0.37 | 2.80 |    | 4  |    |
| bananas               | 0.33 | 0.16 | 0.55 |    | 2  |    |
| blueberries           | 0.27 | 0.19 | 0.45 |    |    |    |
| cantaloupe            | 0.36 | 0.26 | 0.45 |    |    |    |
| cherries              | 0.29 | 0.23 | 0.49 |    | 1  |    |
| cranberries           | 0.33 | 0.16 | 0.55 |    |    |    |
| grapes                | 0.73 | 0.08 | 13.49 |    |    |    |
| honeydew              | 1.05 | 0.84 | 1.26 |    | 1  |    |
| kiwi                  | 1.03 | 0.84 | 1.40 |    | 2  |    |
| mangoes               | 0.60 | 0.46 | 0.77 |    |    |    |
| papaya                | 0.31 | 0.28 | 0.45 |    | 2  |    |
| peaches               | 0.03 | 0.26 | 0.45 |    |    |    |
| pears                 | 0.29 | 0.25 | 0.62 |    |    |    |
| pineapples            | 0.35 | 0.16 | 0.55 |    |    |    |
| plums                 | 0.33 | 0.16 | 0.55 |    |    |    |
| raspberries           | 0.40 | 0.37 | 0.51 |    |    |    |
| strawberries          | 0.33 | 0.12 | 0.51 |    |    |    |
| watermelon            | 0.12 | 0.12 | 0.12 |    |    |    |
| Processed fruit       |    |    |    |    |    |    |
| canned fruit          | 0.73 | 0.08 | 13.49 |    |    |    |
| frozen fruit          | 8.87 | 0.75 | 13.49 |    |    |    |
| dried fruit           | 0.88 | 0.57 | 1.67 |    |    |    |
| fruit juices          | 0.40 | 0.37 | 0.51 |    |    |    |
| Fresh vegetables      |    |    |    |    |    |    |
| artichokes            | 0.33 | 0.12 | 0.51 |    |    |    |
| asparagus             | 0.12 | 0.12 | 0.12 |    |    |    |
| bell peppers          | 0.53 | 0.09 | 1.75 |    |    |    |
| Vegetable                  | C     | R     | E     | Category          |
|----------------------------|-------|-------|-------|-------------------|
| cauliflower               | 0.39  | 0.33  | 0.47  |                   |
| celery                    | 0.73  | 0.08  | 13.49 | all fresh veg     |
| collards                  | 0.33  | 0.12  | 0.51  | brassicas         |
| sweet corn                | 0.73  | 0.08  | 13.49 | all fresh veg     |
| cucumbers                 | 0.66  | 0.08  | 2.13  |                   |
| eggplant                  | 1.30  | 0.64  | 2.92  |                   |
| escarole & endive         | 1.46  | 1.17  | 1.75  |                   |
| garlic                    | 0.33  | 0.09  | 1.75  | roots             |
| kale                      | 0.33  | 0.12  | 0.51  | brassicas         |
| head lettuce              | 1.08  | 0.13  | 4.37  | lettuce           |
| romaine & leaf lettuce    | 1.08  | 0.13  | 4.37  |                   |
| lima beans                | 0.73  | 0.08  | 13.49 | all fresh veg     |
| mushrooms                 | 0.73  | 0.08  | 13.49 | all fresh veg     |
| mustard greens            | 0.33  | 0.12  | 0.51  | brassicas         |
| okra                      | 0.73  | 0.08  | 13.49 | all fresh veg     |
| onions                    | 0.39  | 0.10  | 0.77  |                   |
| potatoes                  | 0.21  | 0.09  | 0.47  |                   |
| Pumpkin                   | 0.09  | 0.09  | 0.09  | squash            |
| Radishes                  | 0.33  | 0.09  | 1.75  | roots             |
| snap beans                | 0.73  | 0.08  | 13.49 | all fresh veg     |
| Spinach                   | 0.13  | 0.11  | 0.27  |                   |
| Squash                    | 0.09  | 0.09  | 0.09  |                   |
| sweet potatoes            | 0.33  | 0.09  | 1.75  | roots             |
| Tomatoes                  | 0.67  | 0.28  | 1.63  |                   |
| turnip greens             | 0.33  | 0.12  | 0.51  | brassicas         |
| Processed vegetables      |       |       |       |                   |
| Canned                    | 1.10  | 0.73  | 1.52  |                   |
| Frozen                    | 1.44  | 0.98  | 2.28  |                   |
| processed and dehydrated  | 1.30  | 0.60  | 2.50  | processed veg     |
| Legumes                   | 0.78  | 0.35  | 1.39  |                   |
| Fluid milk                | 1.34  | 0.99  | 2.05  |                   |
| Other dairy products      |       |       |       |                   |
| Yogurt                    | 2.02  | 1.26  | 2.91  |                   |
| total cheese              | 9.78  | 6.58  | 16.32 |                   |
| cottage cheese            | 1.80  | 1.80  | 1.80  |                   |
| ice cream and ice milk    | 3.10  | 3.10  | 3.10  |                   |
| other frozen dairy        | 3.10  | 3.10  | 3.10  | ice cream         |
| Evap. condensed milk      | 3.20  | 3.20  | 3.20  |                   |
| dry milk products         | 10.40 | 10.40 | 10.40 |                   |
### Table S2: List of revised commodity values that have been modified in order to reduce potential for double counting.

Note that meats are presented on an edible, boneless weight basis (modified with permission from Heller and Keoleian, 2015).

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| Commodity                           | # of entries | kg CO₂e/kg | Avg | Min | Max | Comments                  |
|-------------------------------------|--------------|------------|-----|-----|-----|---------------------------|
| half and half (dairy + fat portion) | 3.77         | 2.08       | 5.93|     |     | light & heavy cream       |
| eggnog (dairy + fat portion)        | 3.77         | 2.08       | 5.93|     |     | light & heavy cream       |
| light & heavy cream                 | 3.77         | 2.08       | 5.93|     |     |                           |
| sour cream                          | 2.60         | 2.60       | 2.60|     |     |                           |
| cream cheese                        | 1.92         | 1.34       | 2.50|     |     |                           |
| Meat                                | 20.15        |            |     |     |     |                           |
| Beef                                | 26.45        | 8.00       | 49.80|     |18  |                           |
| Veal                                | 7.80         | 6.90       | 8.70|     |     |                           |
| Pork                                | 6.87         | 4.30       | 11.52|     |     |                           |
| Lamb                                | 22.90        | 13.10      | 36.00|     |     |                           |
| poultry                             | 5.05         | 2.90       | 8.13|     |     |                           |
| Fish and seafood                    |              |            |     |     |     |                           |
| fresh & frozen fish                 | 3.83         | 2.26       | 7.88|     |     |                           |
| fresh & frozen shellfish            | 11.74        | 0.09       | 21.00|     |     |                           |
| canned fish & shellfish             | 4.11         | 1.81       | 7.32|     |     |                           |
| cured fish                          | 4.11         | 1.81       | 7.32|     |     | canned fish              |
| eggs                                | 3.54         | 1.60       | 6.42|     |     |                           |
| Nuts                                |              |            |     |     |     |                           |
| peanuts                             | 1.94         | 1.26       | 2.63|     |     |                           |
| total tree nuts                     | 1.17         | 0.94       | 1.40|     |     |                           |
| Added sugar and sweeteners          | 0.96         | 0.40       | 1.40|     |     |                           |
| Added fats and oils                 |              |            |     |     |     |                           |
| butter                              | 11.92        | 7.20       | 34.32|     |     |                           |
| margarine                           | 1.36         | 1.10       | 1.66|     |     |                           |
| lard & beef tallow                  | 11.92        | 7.20       | 34.32|     |     | butter                    |
| shortening                          | 2.40         | 1.92       | 2.88|     |     |                           |
| salad and cooking oils              | 1.63         | 0.88       | 2.59|     |     |                           |
| other added fats & oils             | 6.30         | 0.88       | 34.32|     |     | all fats & oils           |

1This column indicates the number of studies that have been included in calculating the average for an individual food. When no direct match has been found, the column indicates the proxy group that has been chosen. Categorical proxies (e.g., “stone fruits”) are an average of all foods that fit the category. Cases where a unique minimum and maximum exist with only one study reported in the average are from single studies that report a range of values.
| Commodity                        | Total Produced | Retail level availability | Retail level losses | Consumer level availability |
|---------------------------------|----------------|---------------------------|---------------------|----------------------------|
| Beef                            | 10kg           | 40                        | 40                  | 40                         |
| Chicken, at farm gate           | 32             | 4.19                      | 1.79               | 10.66                      |
| Chicken, through to processing  | 14             | 3.24                      | 2.38               | 5.22                       |
| Pork, through to processing      | 22             | 4.88                      | 3.40               | 7.54                       |
| Cheese, through to processing   | 7              | 9.97                      | 8.09               | 12.35                      |
| Fluid milk, through to processing| 9              | 1.32                      | 0.94               | 1.73                       |
| Sweeteners                      | 0.66           |                           |                     | Weighted average of honey, sugar & corn syrup; weighted by annual consumption - as a result no uncertainty range provided |
| Eggs, at farm gate               | 25             | 3.29                      | 1.42               | 7                          |

Figure S2: Uncertainty analysis of dietary commodities with high greenhouse gas emission intensities

Table S3: Summary of 2010 per capita commodity consumption from the Loss-Adjusted Food Availability database, for measured stages of consumption
|                                | Non-edible losses | Consumer level losses | Consumed |
|--------------------------------|-------------------|-----------------------|----------|
| Grain products                 | 0.43              | 16.66                 | 60.77    |
| Fresh fruit                    | 13.71             | 13.65                 | 21.44    |
| Processed fruit                | 0                 | 4.31                  | 32.45    |
| Fresh vegetables               | 11.66             | 18.81                 | 40.25    |
| Processed vegetables           | 0                 | 7.8                   | 34.07    |
| Fluid milk                     | 0                 | 15.43                 | 54.02    |
| Other dairy products           | 0                 | 8.54                  | 32.86    |
| Meat                           | N/A\(^1\)         | 10.58                 | 33.66    |
| Poultry                        | N/A\(^1\)         | 6.19                  | 24.74    |
| Fish and seafood               | 0                 | 2.17                  | 4.29     |
| Eggs                           | 1.57              | 3.01                  | 8.51     |
| Nuts                           | N/A\(^1\)         | 0.42                  | 4.19     |
| Added sugar and sweeteners     | 0                 | 17.98                 | 35.23    |
| Added fats and oils            | 0                 | 6.61                  | 23.47    |

\(^1\)Inedible portions of meats, poultry, fish and nuts are accounted for prior to the retail level; i.e., these foods are presented as boneless-equivalent, edible weight, or shelled basis.

There is considerable variation across literature reported emissions with important meat and dairy commodities. This reflects, in part, real variation in production practices for these foods, as well as uncertainty introduced by data quality and methodological choices. As the underlying per capita food...
consumption data does not differentiate production practices, a more refined assignment is not possible in this study. US-specific data are not available for all commodities, and reliance on single or limited US-specific studies may introduce biases that do not represent the true variability that is likely to be seen across production practices.

Food loss and related emissions occurring between farm and primary processing are assumed to be captured in individual LCA studies, with any losses between primary processing and retail assumed to be negligible.

Some data were not available for the year 2010 (discussed below) and therefore were assumed to be correlated with population or economic activity, and estimated accordingly. Per capita emissions calculated from data sources use intercensal population on July 1st (309,326,295); as a result, an assumption of correlation with population, as well as zero-growth with any other independent variables is inherent.

**S1.2 Packaging Materials**

GHG emission from packaging materials are calculated using the following equation

\[ GHG_{PM} = m_i \times FP_i \times EI_{i,j} \]

where \( m_i \) is the total weight of packaging of material \( i \) disposed of in a given year, \( FP_i \) is the fraction that is food packaging, \( EI_{i,j} \) is the emissions intensity of material \( i \) from source \( j \) (either recycled or virgin).

Packaging used for food products is derived from the US EPA’s 2010 Municipal Solid Waste factsheet (Table 2), using the provided disaggregation of material types used in packaging and containers. Fractions of these total that are used for food packaging are taken from reports and personal communication from the industry groups (Table S5). Emissions factors associated with these, along with recycled content taken from US EPA WARM factsheets for aluminum, glass, steel, HDPE.

| Material | Weight Disposed (Mt) | Source | Notes |
|----------|----------------------|--------|-------|
| Steel    | 3                    | 4      | From Table 2, "Containers & Packaging" |
| Aluminum | 2                    | 4      | From Table 2, "Containers & Packaging" |
| Glass    | 9                    | 4      | From Table 2, "Containers & Packaging" |
| Food Contact Paper & Paperboard | 3 | 5 | see p.4; assumed this represents all paper used in food packaging |
| LDPE     | 1.5                  | 4,6    | Used value of 13.7 Mt along with share of resins from 6 |
| HDPE     | 3.6                  |        |       |
| PP       | 2.8                  |        |       |
| LLDPE    | 2.7                  |        |       |
| PET      | 2.5                  |        |       |
| PS       | 0.7                  |        |       |
Table S5: Containers and packaging used by food industry

| Container Material | Default | Min  | Max  | Comments                                                                                     |
|--------------------|---------|------|------|----------------------------------------------------------------------------------------------|
| Steel              | 66%     | 66%  | 66%  | Can Manufacturer's Institute, 2010 P.20, using (food cans - pet food) divided by (food cans + general packaging) |
| Aluminum           | 90%     | 50%  | 95%  | Discussions with Hank Sattlethight from the Aluminum Association suggest it is likely the food industry purchases the majority of containers and packaging, with a high estimate of 90%; a low estimate would be based on the 50% figure from Marsh and Bugusu. |
| Glass              | 90%     | 50%  | 95%  | Author’s estimate for default and max, min uses                                                |
| Paper              | 50%     | 50%  | 50%  | 50% figure from                                                                                  |
| LDPE               | 42%     | 42%  | 50%  | 42% uses the 2010 PE film resin data for from American Chemistry Council (Vallianos, 2015; personal communication); 50% from |
| HDPE               | 42%     | 42%  | 50%  | 42% uses the 2010 PE film resin data for from American Chemistry Council (Vallianos, 2015; personal communication); 50% from |
| PP                 | 42%     | 42%  | 50%  | 42% uses the 2010 PE film resin data for from American Chemistry Council (Vallianos, 2015; personal communication); 50% from |
| LLDPE              | 42%     | 42%  | 50%  | 42% uses the 2010 PE film resin data for from American Chemistry Council (Vallianos, 2015; personal communication); 50% from |
| PET                | 90%     | 50%  | 95%  | Author's estimate for default and max, min uses                                                |
| PS                 | 50%     | 50%  | 50%  | Author’s estimate for default and max, min uses                                                |

Quantities of total containers and packaging used in 2010 that are recycled or virgin are estimated from the source reduction factor datasheets for the USEPA WARM model. In instances where no estimates are provided (PP, HDPE, PS, LLDPE), it is assumed that the quantity of material recycled is negligible. For steel, USEPA "maximum" values of 50% and 20% are used as the default and minimum values, with Gitlitz reporting an average US value of 67.1%. Default aluminum recycling rate is taken from the
minimum value Gitlitz and maximum value from US EPA. All other values are taken from US EPA (2015) with default values being the average of range of estimates from the meta-review, if provided. It should be noted that changes made to electricity grid emissions intensity in the tool will not be reflected in the packaging material emissions intensities used here (i.e., grid intensity assumed by US EPA applies).

**Table S6: Current recycling rates for various food packaging materials**

| Material     | Default | Max  | Min  | Source         |
|--------------|---------|------|------|----------------|
| Steel        | 44%     | 67%  | 20%  | USEPA 2015     |
| Aluminum     | 59%     | 68%  | 50%  | USEPA 2015     |
| Glass        | 23%     | 23%  | 23%  | USEPA 2015     |
| Paper        | 35%     | 35%  | 35%  | USEPA 2015     |
| LDPE         | 0%      | 0%   | 0%   | USEPA Warm, 2015 |
| HDPE         | 13%     | 15%  | 10%  | USEPA Warm, 2015 |
| PP           | 0%      | 0%   | 0%   | USEPA Warm, 2015 |
| LLDPE        | 0%      | 0%   | 0%   | USEPA Warm, 2015 |
| PET          | 7%      | 10%  | 3%   | USEPA Warm, 2015 |
| PS           | 0%      | 0%   | 0%   | USEPA Warm, 2015 |

**Table S7: GHG emission intensities associated with virgin packaging materials**

| Material                           | Default | Units                  | Source         |
|------------------------------------|---------|------------------------|----------------|
| Steel                              | 4.05    | t CO₂e / t material    | 1: exhibit 11  |
| Aluminum                           | 12.22   | t CO₂e / t material    | 1: exhibit 11  |
| Glass                              | 0.66    | t CO₂e / t material    | 1: exhibit 19-18 |
| Virgin Paper (Office Paper)        | 1.09    | t CO₂e / t material    | 1: Exhibit 13  |
| LDPE                               | 1.98    | t CO₂e / t material    | 1: exhibit 8   |
| HDPE                               | 1.73    | t CO₂e / t material    | 1: exhibit 8   |
| PP                                 | 1.71    | t CO₂e / t material    | 1: exhibit 8   |
| LLDPE                              | 1.74    | t CO₂e / t material    | 1: exhibit 8   |
| PET                                | 2.48    | t CO₂e / t material    | 1: exhibit 8   |
| PS                                 | 2.76    | t CO₂e / t material    | 1: exhibit 8   |

**Table S8: GHG emission intensities associated with recycled packaging materials**

| Material | Default | Units                  | Source |
|----------|---------|------------------------|--------|
| Steel    | 2.05    | t CO2e / t material    | 1      |
| Aluminum | 2.19    | t CO2e / t material    | 1      |
| Glass    | 0.35    | t CO2e / t material    | 1      |
### S1.3 Secondary Processing

A tabulation of emissions related to secondary processing (i.e., food manufacturing related to further modifying primary products such as flour, processed produce, or pasteurized milk) is based on emissions associated with refrigerant leaks and energy consumption of this sector.

\[ \text{GHG}_{sp} = \sum_r F_r \times GWP_r + \sum_{i,j} E_{Ci,j} \times EI_j \]

where \( F_r \) are the fugitive emissions associated with refrigerant \( r \), \( GWP_r \) is the global warming potential of refrigerant \( r \), \( E_{Ci,j} \) is the consumption of energy source \( j \) from food processing sector \( i \), and \( EI_j \) is the emissions intensity of energy source \( j \).

Refrigerant leakage is obtained from 2010 data for industrial process refrigerant from the 2014 submission of the US National Submission to the United Nations Framework Convention on Climate Change (CRF Table 2(II).FS1). The share of industrial process refrigeration is assumed to be the same as the food share of cold storage (88%; Jones Lang LaSalle IP). GHG emissions associated with refrigerants are taken from US EPA.

Energy consumption by fuel type of the secondary processing sector is calculated from the values for the entire food manufacturing sector in the 2010 Manufacturing Energy Consumption Survey. The quantities are scaled to represent secondary processing by the using cost of fuel and quantity of electricity purchased by these processor, using the 2012 Economic Census. Subsectors that are identified to be secondary processing are shaded in Table S9. Note that not all secondary processing sectors are shaded below (e.g., cheese manufacturing, peanut butter, produce canning, ice cream), as these were captured in the meta review of the LCA studies and quantified in the loss-adjusted food availability data.

**Table S9: NAICS Classifications of food manufacturing used in 2010 energy demand estimates, with relevant secondary processing sectors cells shaded**

| Dog and cat food manufacturing | Specialty canning         | Tortilla manufacturing |
|-------------------------------|---------------------------|------------------------|
| Other animal food             | Dried and dehydrated food | Roasted nuts and peanut |
S1.4 Distribution

Greenhouse gas emissions that are quantified from the distribution of food include refrigeration leakage from cold storage and energy demand, as well as trucking associated with shipping processed food.
\[ \text{GHG}_d = EC_e \times EI_e + \sum_r F_r \times GWF_r + \sum_j D_j / FE \]

where \( EC_e \) is the electricity demand of cold storage from food, \( EI_e \) is the emissions intensity of the grid, \( D_j \) is the transport distance of a food product, and \( FE \) is the average fuel economy of transportation.

Transportation emissions are calculated using mileage taken from US DoT\textsuperscript{15}. Categories included that are assumed to capture emissions beyond the meta-review are listed in Table S10, providing an estimate of post-primary processing for food road freight of 10.4% of total 2002 US trucking miles. Mileage associated with transport from farm gate to primary processing industries are assumed to be accounted for in the meta-review of LCA studies and are excluded from the mileage total for distribution. Estimates of 2010 trucking data and fuel economies for single-unit and combination trucks from \textsuperscript{16} are used to calculate diesel consumption. GHG emissions are the product of this diesel consumption estimate, the 10.4% fraction of trucking miles calculated using the data in Table S10, and the emission intensity of diesel, providing an upper boundary estimate of 182 kg CO\textsubscript{2}e/cap. As an alternate calculation, 2010 GHG emissions from trucking are taken from US Department of Transportation\textsuperscript{15}, and again scaled by the post-primary food fraction of mileage to provide a lower boundary estimate of 146 kg CO\textsubscript{2}e/cap. The primary estimate used is the average of these two.\textsuperscript{15} It is assumed that transportation of prepared foods (i.e., post-primary processing) by other modes of transportation are negligible. There is some potential for double counting with these transportation emissions, as sectors are not demarcated using NAICS classifications.

\textbf{Table S10: Summary of US Department of Transportation Data on Truck Transportation for Relevant Food Transportation, 2002 (adapted from US DoT, 2013)}

| Relevant Transportation Beyond Meta-review Boundaries | Truck Transportation (km) |
|------------------------------------------------------|---------------------------|
| All other packaged foodstuffs                        | 11,054,000,000            |
| Meat, seafood and their preparations                | 4,918,000,000             |
| Bakery and milled-grain products                    | 5,718,000,000             |
| Alcoholic beverages                                 | 2,202,000,000             |
| Total US Trucking Miles (2002)                       | 24,399,000,000            |

Energy demand from cold storage is calculated as the product of US mid-west cold storage system specific energy demand (48 kWh/m\textsuperscript{3}) and US cold storage volume in Dec 2009 (125,500,000 m\textsuperscript{3})\textsuperscript{17,18}. The fraction of this that is used for storing food is assumed to be 88%, taken from Jones Lang LaSalle IP.\textsuperscript{11}

Refrigerant leakage from cold storage and refrigerated transport are taken from US EPA (CRF, Table 2(II).FS1).\textsuperscript{10} The fraction of commercial refrigeration that is cold storage is assumed to be 10-40% (with retail refrigerant leakage contributing the remaining 60-90%), based on an estimate from a US EPA official responsible for quantification for the US National Inventory Report (Goodwin, 2015; personal communication). An average of 25% was applied for the cold storage share for the primary estimate. The fraction of refrigerated transport emissions (totally 15.8 Mt CO\textsubscript{2}e in 2010) that is used for food is assumed to be the same as the fraction of cold storage that is used for food (88%).\textsuperscript{11}
**S1.5 Retailing**

Energy consumption and refrigerant leakage are considered for retail food GHG emissions, considering supermarket and warehouse club retailers.

\[
GHG_{ret} = \sum_r F_r \times GWP_r + \sum_{i,j} EC_{i,j} \times EI_j
\]

In this case, \(i\) is the type of retail outlet (supermarket or warehouse club). Energy consumption is estimated based on 2011 estimates of US supermarkets and warehouse clubs/supercentres, which contributed to 80% of food-at-home sales in 2010\(^{19,20}\). Specific energy demand (natural gas and electricity) for supermarkets are taken from ICF International\(^{21}\), while a range of specific electricity demand for warehouse clubs are taken from the average of a UK data sample of 150 UK retail outlets ranging in size from 5,000 to 10,000 \(m^2\) \(^{21,22}\). Average floor area for these types of retail outlets are presented in Table S11, based on the revenue-weighted average of Costco and Sam’s Club stores, which comprised 87% of sectoral revenue in 2015\(^{23}\).

**Table S11: Data on Supermarket and Warehouse Club and Specific Energy Demand, with lower and upper estimates presented where available**

|                       | Primary Estimate | Lower Estimate | Upper Estimate | Source |
|-----------------------|------------------|----------------|----------------|--------|
| **Supermarket**       |                  |                |                |        |
| Number of Outlets, 2011 | 64,400           |                |                | 19     |
| Average Floor Area \(m^2\) | 4,300            |                |                | 24     |
| Specific Electricity Demand \(kWh/m^2\) | 552              |                |                | 21     |
| Specific Natural Gas Demand \(m^3/m^2\) | 0.34             |                |                | 21     |
| **Warehouse Clubs**   |                  |                |                |        |
| Number of Outlets, 2011 | 4600             |                |                | 19     |
| Average Floor Area \(ft^2\) | 16,000           |                |                | 23,25,26 |
| Specific Electricity Demand \(kWh/m^2\) | 765              | 660            | 870            | 22     |
| Specific Natural Gas Demand \(m^3/m^2\) | 0.34             |                |                | 21     |

**S1.6 Food Service**

\[
GHG_{sp} = \sum_j EC_j \times EI_j
\]

where \(j\) is the energy source (natural gas or electricity).
Food service energy demand is calculated using floor area data from the Commercial Building Energy Consumption Survey 27,28 linearly interpolating 2010 floor area from 2003 and 2012 data, providing a value of 166 Mm². Specific energy demand (per unit of floor area) is taken from the 2003 survey and held constant for 2010, providing demand of 231 and 280 PJ for natural gas and electricity, respectively. Refrigeration emissions are assumed to be captured within the distribution emissions.

**S1.7 Grocery Trips**

Driving trips between households and food retail have been identified as a potentially significant source of GHG emissions 29. A number of jurisdictions have begun to promote grocery delivery as a means by which GHG mitigation can be achieved 30. While there is potential for multi-purpose trips adding uncertainty the total annual mileage that can be allocated to these grocery trips, the assumption made here is that these are single-purpose trips.

Annual GHG emissions from driving are calculated using literature values as the product of annual grocery driving trips, average trip distance, fuel economy, and fuel emissions factors.

\[ \text{GHG}_{gt} = T \times D_t \times FE \times EI \]

Where \( T \) is the number of annual trips per person, \( D_t \) is the trip distance, \( FE \) is the 2010 average fuel economy of cars and light trucks, and \( EI \) is the emissions intensity of gasoline. The Food Marketing Institute suggests 2.1 household grocery trips made per week (with a +/-50% uncertainty range applied), which is consistent with a Puget Sound study 24,31. Trips per household is divided by Census data on average household size (2.6) to convert this to per capita data 32.

The number of trips made by automobile are weighted based on the national urban:suburban ratio (40:60; Mather et al 2011). The Puget Sound study is applied again for estimating share of trip by automobile based on urban form, 76.7% and 87.3% in urban and suburban areas, respectively 31. Mean distance to grocery stores (1.77 miles) is taken from Morland and Evenson (2009), taken from surveys in Forsyth, NC and Jackson, MS. 35 The maximum distance assumed traveled was 10.3 km, which was the average vehicle trip length for shopping in the 2009 National Household Travel Survey. 36

For energy consumption, estimates of average vehicle fuel economy for cars (22.5 mpg) and light trucks (18 mpg) on the road are taken from Davis et al. 16 An approximation of the fraction of cars and light trucks on the road in 2010 is developed from their respective shares of total sales between 2000-2010 (58:42, respectively 37, giving a weighted average fuel economy of 20.6 mpg. These data are summarized in Table S12.

The main article refers to an extreme scenario where trip emissions could be as high as 370 kg CO₂e/cap; this would employ an average trip length of 7.0 miles \( (38, \text{for “errands”}) \), 87.3% of trips made by automobile 31, and 3.15 trips per week (50% increase on Food Marketing Institute estimate 34).

| Trip Data | Current Estimate | Lower Estimate | Upper Estimate | Source |
|-----------|------------------|----------------|----------------|--------|
|           |                  |                |                |        |
S18 Household Storage and Preparation

Emissions from household storage of foods are taken from 2014 estimates of electricity consumption of freezers and refrigerators adjusted to 2010 estimates using national population data, along with annual refrigerant loss.  

\[ GHG_{dom} = \sum_r F_r \times GW_{r} + \sum_{i,j} EC_{i,j} \times EI_{j} \]  

where \(i\) is the energy end use (refrigerators, freezers, cooking appliance), and \(j\) in this case is the domestic energy source (natural gas or electricity).

Cooking emissions from electricity and natural gas are calculated using US EIA estimates.

S1.9 Food Waste Disposition

Food waste is assumed to be disposed using the methods presented in Table S13. Non-edible waste components (e.g., bone) are assumed to be disposed of per the weighted average (by mass) of the other three waste streams. Donated food is assumed completely consumed. Uses for direct land application, animal feed, and biofuel production are assumed to be carbon neutral, as are emissions from incineration. Energy production from food waste incineration is not included.

Table S13: Disposition of waste streams from various sources

| Waste Management Method | Household | Retail | Farm to Retail | Non-Edible |
|-------------------------|-----------|--------|----------------|------------|
| Composting              | 3%        | 10%    | 2%             | 4%         |
| Anaerobic Digestion     | 0%        | 4%     | 0.1%           | 0%         |
| Donated                 | 0%        | 13%    | 5.7%           | 2%         |
| Landfilled              | 97%       | 58%    | 5.7%           | 92%        |
| Animal Feed             | 0%        | 11%    | 82.4%          | 1%         |
| Direct Land             | 0%        | 3%     | 3.3%           | 0%         |
S1.9.1 Landfill Emissions

Landfill gas (LFG) emissions from food waste disposal is calculated using the methane commitment approach from the Global Protocol for Greenhouse Gas Emissions Inventories for cities.\(^4\) Methane generation potential \((L_o \text{ in } \text{t CH}_4/\text{t MSW landfilled})\) is calculated as

\[
L_o = MCF \times DOC \times DOC_f \times F \times 16/12 \quad (S2)
\]

where \(MCF\) is the methane correction factor, \(DOC\) is the degradable organic carbon content of food waste (or dry sludge), \(DOC_f\) is the fraction of \(DOC\) that is degraded, \(F\) is the fraction methane in landfill gas, \(16/12\) is the stoichiometric ratio between methane and carbon.

\[
CO_2 \text{ emissions} = MSW_x \times L_o \times f_{rec} \times OX \times GWP_{CH_4} \quad (S3)
\]

where \(MSW_x\) is the total food waste (t) deposited in landfill in a given year, \(f_{rec}\) is the fraction of total methane that is collected through landfill gas collection systems, \(OX\) is the fraction of that is oxidized through landfill covers, and \(GWP_{CH_4}\) is the global warming potential of methane including feedbacks (34;Myhre et al, Table 8.7).\(^4\)

Food waste generated is based on estimates from Heller and Keoleian which are, in turn, from data from loss-adjusted food availability data series for 2010.\(^3\) The share of waste produced that is sent to landfill is taken from various sources (presented in Table S14).

### Table S14: Parameters used in the calculation of GHG emissions from landfilled food waste

| Assumed Value               | Min  | Max  | Source                        |
|-----------------------------|------|------|-------------------------------|
| DOC (food)                  | 0.15 | 0.08 | 0.2  | 43                           |
| DOC (dry sludge)            | 0.45 | 0.4  | 0.5  | 43                           |
| MCF                         | 1    | 0.9  | 1    | 43                           |
| DOC dissimilated            | 0.6  | 0.6  | 0.77 | 44,45                        |
| \(F\)                       | 0.5  | 0.4  | 0.6  | 43                           |
| Recovered CH\(_4\)         | 0.6  |      |      | Calculated from 46           |
| OX                          | 0.04 | 0    | 0.1  | Calculated from 46           |
| % Farm-to-Retail Landfilled | 0.06 |      |      | 47 - Figure 2, 2013 data; assumed the same for production and manufacturing side |
| % Retail Landfilled         | 0.58 |      |      | 47 - Table 3, 2011 data      |
| % Consumer Landfilled       | 0.97 |      |      | 4                            |
% Non-Edible Landfilled | 0.76 | Assumed weighted average of all other types

Off-site emissions are assumed to be avoided through the generation of electricity from LFG-to-energy operations (4% of all LFG generated in 2010). The 2010 US national average grid emissions factor of 0.56 kg CO₂e/kWh is applied to determine emissions offset by generation from LFG. The lower heating value energy content of methane 50.03 MJ/kg and electric generator efficiency of 36% are applied to calculate total grid electricity that would be offset.

S1.9.2 Food Waste Residues
S1.9.2.1 Composting

Emissions avoided through the reuse of food waste has been calculated to provide clarity on the net climate impact of waste management approaches. Emissions are assumed to be avoided through the replacement of organic fertilisers and improved carbon storage. The 2010 values of food waste diverted from landfill was 24%, with 14% of the total being sent to compost and 1.5% anaerobically digested. Emissions from composting are calculated using a modified form from as

\[ \text{GHG Emissions}_i = (M \times \text{EF}_i) - R \]  

where M is mass of organic waste treated, \( \text{EF}_i \) is the emissions factor for a greenhouse gas i (methane or nitrous oxide resulting from a given treatment option), and R is the amount of gas recovered (applicable to methane). Using IPCC (2006), methane and nitrous oxide emissions factors of 0.004 kg CH₄/kg wet waste and 0.0003 kgNO₂/kg wet waste, respectively, are applied; it is assumed that no methane is recovered.

In this study, 100% of compost produced is assumed to be applied to land. Offsets achieved through the composting of food waste include carbon sink from land application and substitution of inorganic fertilizers (nitrogen, phosphorous, and potassium) by compost. Fertilizer offsets are calculated as

\[ \text{Fertilizer offset} = W_c \sum_i RV_i \times \text{EF}_i \]  

where \( W_c \) is mass food waste composted, i represents a nutrient, \( RV_i \) is the inorganic fertilizer replacement value in weight of the nutrient per unit of compost (kg/kg ww) and \( \text{EF}_i \) is the emissions factor of production of the nutrient. These values are presented in Table S15.

| Assumed Value | Min | Max | Units | Source |
|---------------|-----|-----|-------|--------|
| **Inorganic Fertilizer Replacement Value** | | | | |
| Nitrogen | 0.00285 | 0.0005 | 0.0052 | kg nutrient/kg food | Boldrin et al 2009; Table |
| Phosphorous | 0.00125 | 0.0006 | 0.0019 | kg nutrient/kg food | Boldrin et al 2009; Table |
| Potassium | 0.0039 | 0.0024 | 0.0054 | kg nutrient/kg food | Boldrin et al 2009; Table |
Carbon storage due to land application of compost is assumed to be 0.041 kg CO₂e/kg food waste (Boldrin et al 2009; p.805).

**S1.9.2.2 Anaerobic Digestion**

GHG emissions (methane specifically) from anaerobic digestion of waste in digestion vessels are calculated using Equation S4, using data from Pipatti et al and Møller et al; an emissions factor of 0.004 kg CH₄/kg is used (which is in line with Møller et al, but differs from the Pipatti 2006 default value of 0.001, but lies within the uncertainty range of 0 - 0.008), along with an \( R \) value (fraction recovered) of 0.99. The high \( R \) value corresponds with the suggestion by Pipatti et al that when measures are in place to ensure fugitive emissions are flared, this is assumed to be nearly zero. Additionally, Møller et al suggest further emissions enumeration; CO₂ emissions from on-site diesel combustion at digestion facilities (4.3 g CO₂e/kg of waste digested), as well as N₂O from land application of digestate (0.05 kg CO₂e/kg of waste digested) are also counted.

Emissions offsets are achieved through displaced inorganic fertilizers from land application of digestate and the generation of electricity from methane; these are calculated as in Equation S5 and the method used for calculating LFG electricity generation, respectively (see Table S16 for relevant data). Offsets from carbon storage from land application are assumed to be 0.041kg CO₂e/kg food waste digested (53; p.805).

| Assumed Value | Min | Max | Units | Source |
|---------------|-----|-----|-------|--------|
| **Inorganic Fertilizer Replacement Value** | | | | |
| Nitrogen | 0.00665 | 0.0055 | 0.0078 | kg nutrient / kg food waste treated | 54 |
| Phosphorous | 0.00011 | 0.000075 | 0.00015 | kg nutrient / kg food waste treated | |
| Potassium | 0.00026 | 0.0002 | 0.000325 | kg nutrient / kg food waste treated | |

| Assumed Value | Min | Max | Units | Source |
|---------------|-----|-----|-------|--------|
| **Emissions Factor of Nutrient Production** | | | | |
| Nitrogen | 8.85 | 4.7 | 13 | kg CO₂e / kg N | 55; Table 5 |
| Phosphorous | 1.8 | 0.5 | 3.1 | kg CO₂e / kg N | 55; Table 5 |

**Table S16: Replacement values and emissions factors of nutrients obtained from compost**
It should be noted that in the context of a low-carbon electricity grid, the net benefits of electricity generation from anaerobic digestion and landfill gas will be reduced as the magnitude of the carbon offset is relatively low.

**S1.9.2.3 Nutrient Recovery from Sludge**

Emissions from US sludge production in 2010 is taken from the US Environmental Protection Agency (2015a; Table 7.7), taken as the sum of CH₄ emissions from domestic and food industry wastewater treatment, as well as N₂O from domestic wastewater treatment. Landfill GHG emissions from sludge disposal in landfill are calculated as above. Nitrogen removed with sludge are also taken from US Environmental Protection Agency (2015a), with phosphorous : nitrogen in sludge assumed to be 1:10. Offsets from the land application of sludge from displaced nitrogren and phosphorous inorganic fertilizer are 8.9 and 1.8 kg CO₂e/kg nutrient, respectively (Boldrin et al; Table 5). Carbon storage from this approach is estimated at 0.25 kg CO₂e/kg biosolids (dry). Emissions (N₂O; CH₄ is assumed to be negligible) from land application of sludge are taken as 0.91 kg CO₂e/kg N applied from Brown et al. Share of biosolids that are land applied in 2010 is assumed as 55%.

**S1.10 Emissions Factors Applied**

The following is a list of emissions intensities that applied for various energy sources used in the calculations above.

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**Table S17: Emissions Factors for various secondary energy sources and refrigerants used in food system activities**

| Emissions Factor | Secondary Energy Source | Units       |
|------------------|-------------------------|-------------|
| 0.563            | Electricity             | kg CO₂e / kWh |
| 69.28            | Residual Fuel Oil       | g CO₂e / MJ |
| 74.63            | Distillate Fuel Oil     | g CO₂e / MJ |
| 50.31            | Natural Gas             | g CO₂e / MJ |
| 58.99            | LPG and NGL             | g CO₂e / MJ |
| 89.01            | Coal                    | g CO₂e / MJ |
| 88.75            | Coke and Breeze         | g CO₂e / MJ |
| 0.00             | Other¹                  | g CO₂e / MJ |
| 38.68            | Diesel                  | kg CO₂e / l |
| 21.79            | Gasoline                | kg CO₂e / l |
| 33.38            | Ethanol                 | kg CO₂e / l |
| 32.22            | 10/90 Ethanol/Gasoline  | kg CO₂e / l |
| 3500             | HFC-125                 | kg CO₂e/kg  |
S2 Quantifying Emissions Reduction Potential

S2.1 Urban Agriculture

Urban agriculture is assumed to mitigate emissions relative to conventionally-delivered produce through a reduction in food loss, transportation, distribution, and reduced landfill gas production (due to avoided waste in the food supply chain). Urban agriculture in this instance is defined as open-field production of fruits and vegetables that requires only transportation from retail to household. A reduction in food production required through the conventional food systems that would have otherwise been lost provides an estimate for emissions savings from food loss. To state this another way, emissions associated with conventional production still occur, but the quantity of emissions from food produced and then lost between farm to retail is reduced by the amount produced through urban agriculture.

A reduction in cold storage requirement is assumed through urban agriculture; the fraction of cold storage that is produce is derived from the LAFA, assumed to be total fruits and vegetables produced that require cold storage (fresh fruits, vegetables and fruit juices) divided all perishable food commodities (milk, dairy, meat, seafood, butter, margarine). This gives a value of 45% of all food that is kept in cold storage. It is likely that this is an overestimate, as the LAFA quantities do not include perishable goods resulting from secondary processing.

Emissions associated with transportation of fruits and vegetables are estimated to be 11% of farm to retail emissions by Weber and Matthews. In this case, the emissions intensity of the urban agriculture share of production is assumed to be the average of the literature values obtained from the meta-review for fresh and canned produce. Finally, landfill gas emission mitigation associated with food waste reduction are calculated using the methane commitment methodology for landfill gas emissions.

Annual yields of vegetables are taken from the average of literatures sources, whose yield data are themselves averaged from the various operations described within their research, providing default, high and low values of 2.3, 3.9 and 0.7 kg/m², respectively. Fruit yield is assumed to be 0.56 kg/m², based on . The maximum productive land of urban areas is based on an estimate of percentage of total urban land (275,000 km²) that is vacant of the total urban land area (15% vacant on average, from 70 US cities in 2000). It is assumed in this measure that 50% of this land is used and is suitable for production (which makes this a generous estimate). Fractions of land used for vegetable production are calculated based on current levels of consumer-side consumption and yield data provided above. This is estimated with the relationship

|   | HFC-134a | kg CO₂e/kg |
|---|----------|------------|
| 1430 | 4470 | 124 | 9810 | 675 |

1 asssumed to be carbon neutral (biomass), when applied to secondary processing calculations
\[ f_v = 1 - \frac{T_f}{T_f + \frac{y_f}{y_v}} \]  \hspace{1cm} (S6)

where \( f \) is the fraction of production of a commodity (denoted with subscript \( f \) for fruit or \( v \) for vegetable), \( T \) is the total consumer demand of commodity (taken from the USDA Loss Adjusted Food Availability data); \( f_v \) is the quotient of \( T_v \) and \( T \), and \( y \) is the estimate of yield for that commodity. This is developed from the relationships

\[ A_T = A_F + A_V \]  \hspace{1cm} (S7)

\[ A_x = \frac{T_x}{y_x} \]  \hspace{1cm} (S8)

where \( A_x \) is the land area required for commodity \( x \). Seasonality of crops, site quality (i.e., related soil, water, solar resources), temporal mismatch of production/consumption, and property ownership are also not considered, making the estimated available yields optimistic.

**S2.2 Cultured Meat**

Cultured meats are reported to reduce GHG emissions relative to conventional production, with an emissions intensity of between 1.9 - 2.2 kg CO₂e/ kg of cultured meat. A direct substitution of conventional meat products is assumed, with cultured meat replacing each of these in proportion to their current levels of consumption (i.e., not favoring the substitution of any animal source). The emissions factors of conventional meats are taken from the meta-review described above (presented in Table S18).

**Table S18: Emissions intensities of various meat products, as developed in the meta-review**

| Meat Product | GHG Intensity (kg CO₂e/kg meat) |
|--------------|----------------------------------|
| Beef         | 33.7                             |
| Veal         | 7.8                              |
| Pork         | 5.5                              |
| Lamb         | 22.9                             |
| Poultry      | 4.8                              |

**S2.3 Food Waste Avoidance**

Assumes that food waste avoided fully offsets need for production of and related inputs of current balance of commodities, as well as other upstream inputs that result in emissions. For example, for each unit of mass of food waste avoided, the upstream production requirements are also assumed to be avoided. Greater benefits would be realized by avoiding the waste of animal products, but food products are expected to be preserved according to the current distribution of consumption and no weighting towards higher value or more carbon intensive foods is applied.
S2.4 Improved Recycling of Food Packaging

Under the improved recycling rate scenario, the diversion rates in Table S19 were applied in place of those presented in Table S6.

**Table S19: Changes in diversion rates applied in the improved recycling scenario**

| Material | Current Diversion Rate | Proposed Diversion Rate |
|----------|------------------------|-------------------------|
| Steel    | 44%                    | 70%                     |
| Aluminum | 59%                    | 70%                     |
| Glass    | 23%                    | 50%                     |
| Paper    | 35%                    | 50%                     |
| LDPE     | 0%                     | 0%                      |
| HDPE     | 13%                    | 50%                     |
| PP       | 0%                     | 0%                      |
| LLDPE    | 0%                     | 0%                      |
| PET      | 7%                     | 50%                     |
| PS       | 0%                     | 0%                      |

S2.5 Divert Food Waste from Landfill to Anaerobic Digesters

In assuming increased anaerobic digestion of food, the amount of food waste is assumed unchanged, however, diversion is assumed to be as shown in Table S13 apart from landfilled waste from household and retail are reduced to 47% and 8%, respectively. This then allows for 50% of these waste streams to be directed to anaerobic digestion. Emissions are avoided through a reduction in landfill gas generation, offsets of electricity generation/fertilizer production, and increased soil carbon storage.

S2.6 Apply 90% of Biosolids to Agricultural Land

An increase of biosolids application to agricultural land from 50% to 90% reduces emissions of landfill gas from its diversion from landfill, as well as offsetting energy demands from inorganic phosphorous and nitrogen production. Carbon storage is also considered, as discussed in the section "Nutrient Recovery from Sludge".

S2.7 Reduce Grocery Trips by 50%

Emission reductions from grocery trips used the analysis of Wygonik and Goodchild, where the impact of grocery delivery was examined for three Washington state counties. Their analysis considered randomly allocated destinations (consumers selecting delivery times), as well as optimized delivery to reduce distance travelled (provider selecting delivery times). Their results estimated emissions reductions of 45 and 86%, respectively for these two delivery approaches. These reductions are assumed to be consistently achieved in other cities, and are applied as the lower and upper limits achievable, and the average of the two is applied to a scenario in which a 50% reduction in grocery trips is achieved through deliveries.
**S2.8 Electricity Grid Decarbonisation**
Electricity consumption for the food system is disaggregated for all segments in Figure S1 that are quantified in this study (those that have a solid outline). A decarbonization scenario involves reducing 2010 grid emissions factor of 0.563 kg CO$_2$e/kWh$^6$ to zero.

**S2.9 Meatless Mondays**
This scenario considers annual average per capita meat production level emissions across all types of meat and seafood produces are reduced by $1/7 = 14.3\%$, with this being replaced by legumes (and associated production emissions). Emissions associated changes in cold chain and differences in storage and preparation are not considered.

**S2.10 Replacing 25% of Beef Consumption with Chicken**
Similar to the "Meatless Monday" scenario, beef production emissions are reduced by 25% and the weight of this annual consumption is substituted directly for chicken. As above, emissions associated changes in cold chain and differences in storage and preparation are not considered.
S3 Baseline Emissions

Based on the emissions described above, the following is a summary of the emissions from each sector. Uncertainty estimates are provided where a range could be identified from the literature sources.

Table S20: Summary of emissions calculated from each sector, with uncertainty ranges where calculated

| Sector                                      | Average | Min  | Max  |
|---------------------------------------------|---------|------|------|
| Production & Primary Processing (Meta-Review)|         |      |      |
| Grain products                              | 57.6    | 35.2 | 75.6 |
| Fresh fruit                                 | 33.2    | 13.7 | 68.5 |
| Processed fruit                             | 40.4    | 32.8 | 54.0 |
| Fresh vegetables                            | 46.9    | 12.6 | 231.6|
| Processed vegetables                        | 53.8    | 34.8 | 82.1 |
| Fluid milk                                  | 104.4   | 74.5 | 136.8|
| Other dairy products                        | 246.6   | 202.7| 301.6|
| Meat                                        | 1096.5  | 607.4| 1918.1|
| Fish and seafood                            | 45.8    | 10.0 | 84.8 |
| Eggs                                        | 47.4    | 20.4 | 100.7|
| Nuts                                        | 8.2     | 5.7  | 10.8 |
| Added sugar and sweeteners                  | 39.5    | 39.5 | 39.5 |
| Added fats and oils                         | 115.5   | 68.7 | 262.0|
| Secondary Processing                        | 109.03  | N/A  | N/A  |
| Packaging Materials                         | 114.12  | 77.97| 131.22|
| Distribution                                | 238.50  | 214.55| 264.50|
| Retail                                      | 390.60  | 370.79| 410.41|
| Food Service                                | 179.39  | N/A  | N/A  |
| Grocery Trips                               | 49.41   | 8.05 | 292.96|
| Household                                   | 309.65  | N/A  | N/A  |
| Landfill - Food                             | 445.04  | 164.71| 745.12|
| Landfill - Sludge                           | 26.32   | 18.24| 36.72 |
| Wastewater                                  | 59.16   | N/A  | N/A  |
| Composting\(^1\)                            | 3.24    | -4.71| 9.31 |
| Emissions                                   | 4.75    | 0.40 | 9.51 |
| Fertilizer Offset from Composting           | -0.66   | -0.08| -1.72|
| Carbon stored in land application           | -0.85   | -0.12| -3.39|
| Anaerobic Digestion\(^2\)                   | -0.09   | -0.36| 0.16 |
| Emissions                                   | 0.15    | 0.11 | 0.22 |
| Carbon stored in land application           | -0.14   | -0.03| -0.28|
|                              | Fertilizer Offset from Composting | Offset from Electricity | Total Emissions (kg CO₂e/cap) |
|------------------------------|-----------------------------------|-------------------------|-------------------------------|
|                              | -0.07                             | -0.03                   | -0.12                         |
|                              | -0.03                             | -0.00                   | -0.07                         |
| Total Emissions (kg CO₂e/cap)| 3,846.46                          | 2,669.71                | 5,886.43                      |

¹Net emissions
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