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Supply Chain Greenhouse Gas Emission Factors for US Industries and Commodities

Progress for a Stronger Future

Office of Research and Development
Center for Environmental Solutions and Emergency Response
Land Remediation and Technology Division

Supply Chain Greenhouse Gas Emission Factors for US Industries and Commodities

by

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Foreword

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Gregory Sayles, Director
Center for Environmental Solutions and Emergency Response

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Acronyms and Abbreviations

BEA	Bureau of Economic Analysis
IO	Input-Output
EEIO	Environmentally-Extended Input-Output Model
MRIO	Multi-Regional Input-Output model
USEEIO	US EPA's United States Environmentally-Extended Input-Output Model
GHG	Greenhouse gas
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide
kMT	Thousand metric tons
MMT	Million metric tons
DEF	Direct emission factor
MEF	Margin emission factor
SEF	EEIO-based supply chain emission factor

Executive Summary

Many organizations quantify greenhouse emissions in their value chain. Emissions from purchased goods and services and capital goods, referred to as Scope 3 emissions in the Greenhouse Gas Protocol Scope 3 Accounting and Reporting Standard, represent a significant emissions source for many organizations. To assist in quantifying these emissions, we have developed a comprehensive set of supply chain emission factors covering all categories of goods and services in the US economy. The final factors are available in the Supply Chain Emission Factors for US Industries and Commodities dataset. These factors are intended for quantifying emissions from purchased goods and services using the spend-based method defined in the Greenhouse Gas Protocol Technical Guidance for Calculating Scope 3 Emissions.

This report describes the preparation of those factors with a background on the modeling associated with this preparation, and presents extensive analysis of the factors, including supporting equations and results in two appendices. These factors were prepared using USEEIO models, which are a life cycle models of goods and services in the US economy.

The supply chain emission factors are presented in units of kilogram emissions per US dollar of purchases for a category of goods and services with a defined life cycle scope. Sets of factors covering all sectors of the economy are provided for years from 2010 to 2016 with two levels of sector aggregation. The factors are provided for both industries and commodities, where commodities are equivalent to a category of good or service, and industries are producers of one or more commodities. A set of five data quality scores covering data reliability, temporal, geographical and technological correlation and completeness of data collection is provided along with each factor.

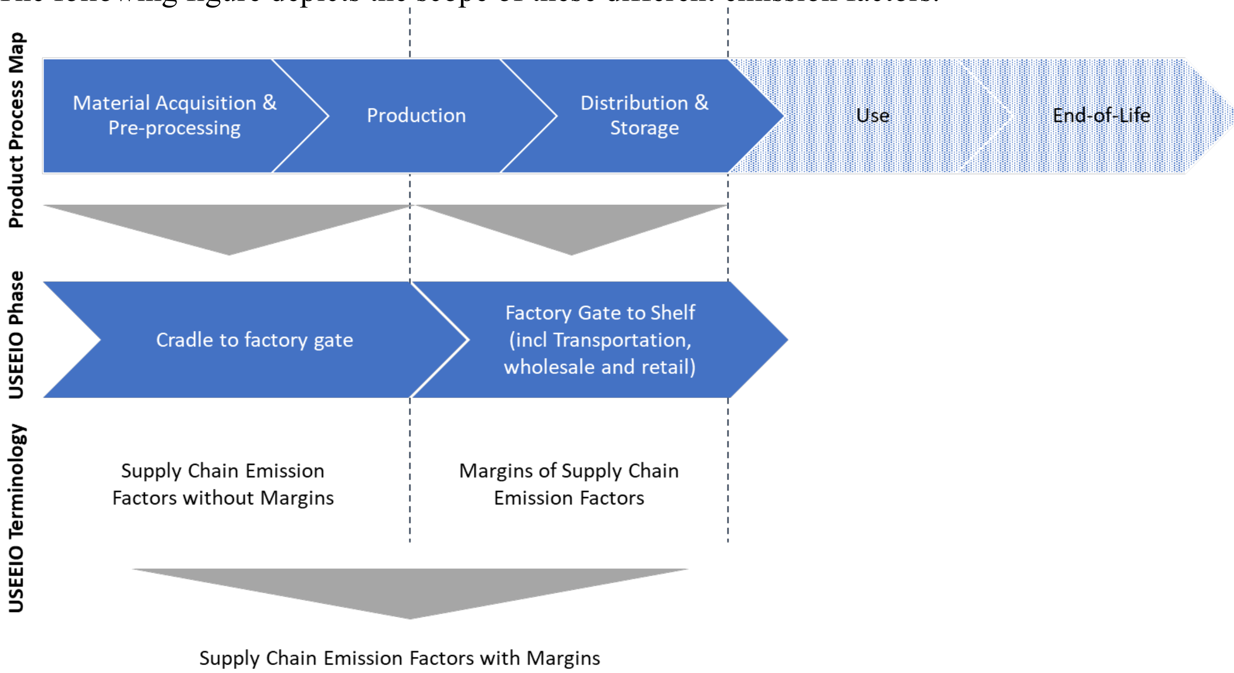
The factors presented are as follows:

1. Supply Chain Emission Factors without Margins: emissions associated with cradle to factory gate

2. Margins of Supply Chain Emission Factors: emissions associated with factory gate to shelf, which includes emissions from transportation, wholesale and retail as well as adjustments for price markups

3. Supply Chain Emission Factors with Margins: emissions associated with cradle to shelf (equal to the sum of the above two factors)

The following figure depicts the scope of these different emission factors.



End users of products will likely find the Supply Chain Emission Factors with Margins most appropriate for their use. Organizations purchasing intermediate products at the factory gate will likely find the Supply Chain Emission Factors without Margins to be most appropriate.

Using a hypothetical example to demonstrate one potential use of a factor, an organization could multiply their total spend on furniture in a given year, for example $/10,000 in 2016, by the 2016 factor for furniture from the summary level commodity model – 0.246 kg CO_2/USD for furniture from cradle-to-shelf – to calculate the Scope 3 CO_2 emissions associated with furniture purchases in their organization, as follows:

$$\$10{,}000 \text{ spent on furniture} * 0.246 \text{ kg } CO_2 \text{ emitted from cradle-to-shelf per dollar spent on furniture} =$$

$$2{,}460 \text{ kg Scope 3 } CO_2 \text{ emissions associated with furniture spending}$$

To calculate other greenhouse gas emissions associated with this same spend category, the organization would multiply this same spend amount by the factors for CH_4, N_2O, and an aggregate factor for other minor GHGs. To then sum these together, an organization would need to first transform emissions of each gas into CO_2 equivalent using a set of global warming potential factors, such as those in Table 1-2 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018.

All factors are associated with limitations and variations in underlying data quality. We encourage the reader to carefully read the report to understand the differences across these sets, underlying assumptions in their calculation, their limitations to decide if they are appropriate for their intended use. If the reader deems the factors are appropriate, this report along with the factor data quality scores will aid in selection of factors best fit for their intended use.

1. Introduction

Producers and consumers are interested in minimizing the potential environmental impact of their production and consumption. Organizations producing goods or services are making strides towards reducing emissions and resource use associated with their activities. However, there is evidence that for some categories of goods and services, the majority of their potential environmental impact may lie 'embedded' in their supply chains. This dominant 'upstream' share of potential impacts has particularly been demonstrated for greenhouse gas (GHG) emissions (Goldhammer et al., 2013; Hertwich and Wood, 2018; Matthews et al., 2008). These are emissions that occurs in the supply chain of a product or service. This phenomenon does not just hold for final consumers. Industries are also consumers, and in some cases it is through this consumption of products used to make or provide the good or service that they are producing where the greater potential impact may be found — and thus the greater opportunity to reduce their footprint.

GHG emissions are the most commonly assessed sources of potential environmental impact by organizations. A complete supply chain GHG assessment for an organization is synonymous with one form of a carbon footprint (Peters, 2010). For organizations, various standards and protocols have been published and define how carbon footprints should be calculated (BSI, 2011; ISO, 2018; WBCSD, 2013). These standards have a variety of scopes, ranging for an entire organization or for a specific product or process. Organizations may use these standards to guide their calculation of GHG emissions and report those to a registry, like the Carbon Disclosure Project (CDP) ("CDP," 2019). The GHG Protocol is likely the most widely used standard by large organizations, as more than 9 of 10 organizations report to the CDP using this protocol (WBCSD, 2019). Organizations often lack data for determining the environmental performance of specific product supply chains, and less so their organization's supply chain emissions. One approach to address this data gap is to provide 'supply chain emission factors' for organizations to use for estimation of these emissions that can be applied to their purchases (DEFRA, 2012; WBCSD, 2013).

1.1. Environmentally-Extended Input-Output Models

One type of model that might serve the purpose of providing supply chain emission factors is an Environmentally-Extended Input-Output (EEIO) model (Huang et al., 2009; Minx et al., 2009). EEIO models are based on economic input-output (IO) tables that represent monetary exchanges between sectors in an economy as well as consumption by final consumers in a balanced accounting framework. EEIO models can represent one region or more than one region. In the latter case, they are referred to as multi-regional input-output models (MRIO). One standard form of IO tables is the supply-use tables, which portrays what commodities are produced by each industry, as well as how commodities are consumed by industries and final consumers. (UN, 2018). The 'Make and Use' form is a similar form adopted by the US Bureau of Economic Analysis (BEA), the federal agency responsible for producing these tables for the US (BEA, 2009). The BEA publishes IO tables annually at two aggregated levels of sectoral detail, 'sector' (~12 sectors) and 'summary' (~70 sectors) levels, and every five years they provide benchmark IO tables at the 'detail' level of sectoral resolution (~400 sectors).

IO tables can be used to create various econometric IO models that can be used for purposes including modeling the economic relationships in a supply chain (Miller and Blair, 2009). IO models are complete in that they cover all industries in an economy, in the sense that every industry is explicitly represented in the model, and in the sense that for each industry, all inputs to production that are purchased, including other goods and services and labor, are captured. When IO tables are paired with environmental data, they can be 'extended' to create EEIO models. EEIO models can reveal environmental relationships in a supply chain. EEIO models can be a form of life cycle inventory models that are used in the practice of life cycle assessment (LCA) to model the potential impacts of goods and services (Sonneman and Vigon, 2011).

While IO models can characterize the production of commodities by industries and their supply chains, they generally do not include coverage of the same commodities as they are used and then later reach an end-of-life. Thus, IO models are appropriate for characterizing production activity within industries from 'cradle to gate' rather than 'cradle to cradle' or 'cradle to grave'. However, additional data can be added to the cradle-to-gate data to model additional impacts associated with 'gate to shelf' distribution, wholesaling and retailing of commodities (Hendrickson et al., 2006).

The use of EEIO models for estimation of supply chain emissions is most appropriate for product groups (Goldhammer et al., 2013) and when assessing supply chain GHG impacts via financial activity data (WBCSD, 2013). EEIO models estimate the energy use and/or GHG emissions from the production and upstream supply chain activities of different sectors and products in an economy (i.e., 'cradle to gate'). The resulting emission factors can then be used to estimate GHG emissions for a specific industry or product category (WBCSD, 2013), like 'furniture manufacturing' or 'furniture'. EEIO models can also be used for 'screening' or 'streamlining' the potential supply chain impact estimation for specific products and supply chains (Huang et al., 2009; Matthews et al., 2008). Doing so allows those estimating supply chain GHG emissions (e.g., companies, institutional purchasers) to direct their supply chain engagement efforts to industries or product categories. Then, for more specific product supply chain accounting, the use of other methods including process-based life cycle inventories, or mixes of EEIO and process-based life cycle inventories, are recommended (Minx et al., 2008; WBCSD, 2013), because EEIO data provide less granularity compared to such other sources of data. On the other hand, use of process-based LCA can underestimate actual supply chain emissions, because supply chain 'cutoffs' (missing inputs in supply chains) are intentionally or unintentionally applied, which results in omitted supply chain emissions (Blanco et al., 2016; Lenzen, 2000).

1.2. USEEIO Model

United States Environmentally-Extended Input-Output (USEEIO) models are a family of EEIO models of the US developed and maintained by the US EPA (Yang et al., 2017). The USEEIOv1.1 model has been used in various applications by researchers, states, municipalities, and organizations. The model components, data and results of USEEIOv1.1 are publicly available in multiple forms (Ingwersen, 2017; Ingwersen and Yang, 2017; Ingwersen et al., 2017; Srocka and Ingwersen, 2019). USEEIOv1.1 is a single region, commodity-based model that uses the BEA 2007 benchmark input-output tables and environmental extensions covering a wide range of resources and emissions. Among the USEEIO environmental extensions are GHG emissions by industry, enabling use of USEEIO for calculation of supply chain GHG emissions. USEEIO includes the impacts of imported commodities in the supply chain; however, these impacts are modeled with the domestic technology assumption, meaning that commodities are assumed to be produced like they are produced domestically.

1.3. Purpose

The purpose of this report is to:

1. Describe the calculation of supply chain GHG emission factors along with direct and margin GHG emission factors using USEEIO models with varying levels of sectoral detail, for the most recently available years, and for both industries and commodities.

2. Evaluate the GHG emission factors and all the intermediate steps toward factor calculation to explicate the factors and how they change across time and through modeling variations.

1.4. Scope of Emission Factors

The supply chain emission factors encompass the initial life cycle phases of a product from material acquisition through manufacture or provision of the good or service.

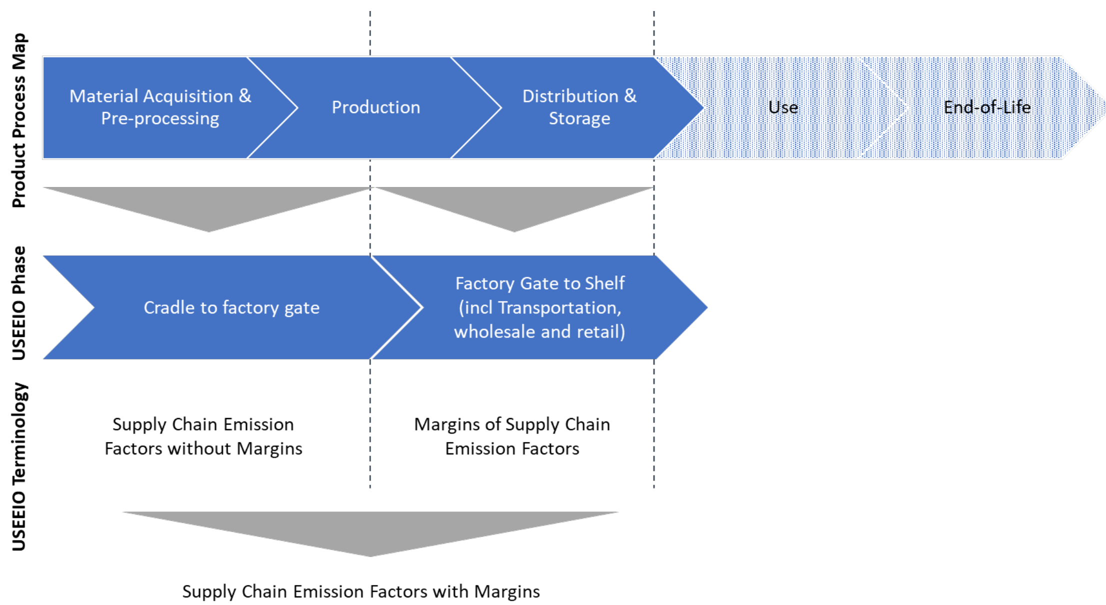


Figure 1: Scope of the supply chain and margin emission factors.

The associated margin emission factors add the emissions associated with transporting, storing and selling the commodity. The use stage of the product and end-of-life emissions are not included in the factors. We also calculated direct emission factors as part of the development of the supply chain emission factors, which represent only on-site emissions associated with the production phase. All emission factors are given in units of kg gas per $ of a commodity of industry for major gases, or kg CO_2-equivalent for minor GHG gases.

2. Methods

Preparing emission factors with an EEIO model requires construction of an appropriate IO model from input-output tables, preparation of a compatible set of environmental data in the form of an environmental satellite table, and final combination of these data and adjustment to reflect price of interest. Some key terms used throughout this report can be found in the Glossary.

2.1. National GHG Totals by Industry

Preparation of the GHG environmental extension data for USEEIO start with the calculation of GHG totals by industry for each GHG for which an emission is reported. We use the model used for the USEEIO v1.1 GHG Satellite table (Ingwersen et al., 2017), later extended by researchers at the Yale University Center for Industrial Ecology (Berrill and Miller, 2019), and then further refined and updated for this study. The model is built into a dynamic model that can provide these totals by industry for years 2010 to 2016, referred to here as the National GHG Industry Attribution model (Yang et al., 2020). This model was updated to use the 2018 US Greenhouse Gas Inventory Report (US EPA, 2018), with numerous additional data sources used to allocate GHG emissions to industries. For an industry sector classification, the National GHG Industry Attribution model uses the 405 detailed industry sectors defined by the BEA in the 2012 input-output tables (BEA, 2019a). The model does not include biogenic CO_2 emissions, or those emissions derived from biomass.

2.2. USEEIO Model Construction

USEEIO model construction starts with creation of a specific form of an input-output model. We use the BEA Make and Use tables (BEA, 2019a) for various years and levels of sectoral detail to create two model forms, the commodity-by-commodity form, and the industry-by-industry form, both based on the industry-technology assumption (Miller and Blair, 2009). The former is used for the commodity-based supply chain factors, and the latter for the industry-based factors. The industry-technology assumption assumes that all commodities produced by a given industry have the same input requirements and same environmental profile, a common assumption in IO models (UN, 2018).

A series of USEEIO models are created to represent years 2010-2016, the commodity-based and industry-based model forms, and at two levels of sectoral detail. Appendix 2 includes a list of all USEEIO models created to calculate supply chain emission factors.

We use the GHG totals by industry from the National GHG Industry Attribution model for years for 2010 to 2016 as the source of GHG emissions by industry. We use the BEA detailed (~400 industries and commodities) and summary level (~70 industries and commodities) IO tables, provided before redefinitions and in producer prices, to construct EEIO models and calculate supply chain factors for each model, as well as many related results. All the levels of industry classification are parametric in the sense that a ‘sector’ can be disaggregated into two or more ‘summary’ level industries, and the ‘summary’ level industries can be disaggregated into two or more detailed levels. Therefore, the GHG totals by industry from the National GHG Industry Attribution model are aggregated for use with ‘summary’ model. We also use the ‘sector’ level classifications as means of summarizing results to make them more readable. A complete list of industries and commodities at the summary and detail level is available in Appendix 3.

We use the 2012 Personal Consumption Expenditures and Private Investment in Equipment bridge tables to derive margin data used both for margin emission factors and price adjustments (BEA, 2019b). These bridge tables are only published every five years. Margins used in this report are available in Appendix 4.

The USEEIO model building and calculation was performed with the useeior v0.1 R package (Li and Ingwersen, 2020). The data quality scores were generated for the same models using the useeiopy v0.1 Python package (Ingwersen, 2020). R software v3.6 (R Core Team, 2019) and RStudio v1 (RStudio Team, 2016) were used with these packages and others (Auguie, 2017; Slowikowski, 2019; Ushey et al., 2019; Wickham, 2016, 2007; Zhu, 2019) to prepare the results. We perform a validation test of the models such that scaling SEFs by total national demand with a variation of the models using only domestic total requirements results in total GHGs equivalent to the national GHG emission totals from the National GHG Industry Attribution model. We describe this procedure in Appendix 1 and summarize results of the validation test in Appendix 10.

2.3. Factor Calculation

The generalized formula for a direct emission factor (DEF) is:

$$DEF_x = GHG_x / output_x \qquad [1]$$

where GHG_x is the total national emission for industry or commodity x in kg in a given year, and $output_x$ is the economic output of the industry or commodity in the same year.

The generalized formula for a supply chain emission factor (SEF) is:

$$SEF_x = DEF_a TR_{aforx} + DEF_b TR_{bforx} + DEF_C TR_{Cforx} + \ldots DEF_C TR_{zforx} \qquad [2]$$

where SEF_x is the supply chain emissions factor for commodity or industry x, DEF is the direct emissions factor in kg/$ for industry or commodity a, TR_a are a total requirement of a to make x in $/$, where $a, b, c \ldots z$ are the commodities or industries that are part of the set of total requirements to make x, and where x is always part of the set or total requirements to make x so that direct emissions are always included.

We also compute margin emission factors, MEF_x , representing factory gate to retail shelf impacts per dollar value of the commodity or industry, x:

$$MEF_x = SEF_d MR_{dforx} + SEF_w MR_{wforx} + SEF_r MR_{rforx} \qquad [3]$$

where MEF_x is the margin emission factor for commodity or industry x, SEF is the supply chain emissions factor in kg/$ for margin components d, distribution, w, wholesale, and r, retail, and MR are the margin amount of a margin component to deliver or sell x in $/$.

The supply chain and other emission factors for a given year are calculated with a model name with that given year which is always the year of the GHG emissions data used. When the year of the economic data was not the same as the GHG year (for detailed models only because of lack of annual data at this level), procedures were used to make dollar year adjustments to align the direct emissions factors with the dollar year of the input-output data. Full details are available in Appendix 1.

In the US economy, like in other economies, industries may produce multiple commodities, some as secondary products or by-products that may have different classifications and are in fact primary products of other industries. Industry-based SEFs, calculated with industry-based models, represent a weighted average of commodities produced by the given industry that span multiple sectors in the models. Commodity-based SEFs, calculated with commodity-based models, represent the commodities regardless of which industry produced them.

We report supply chain and margin emission factors separately, and also combined, where combined they represent cradle-to-shelf emissions per dollar of the given commodity or industry. The complete details on the USEEIO model construction and factor calculation are presented in Appendix 1.

2.3.1. Stepping Through a Supply Chain Emission Factor Calculation

To walk through a supply emission factor calculation, we step through part of the calculation for the supply chain factor for CO_2 of furniture. To make furniture, industries purchases commodities made by other industries. When these purchases are scaled per dollar furniture, they are called their direct requirements. Wood products is the largest direct requirement into furniture purchases, at about 8 cents per dollar. Industries producing wood products purchase $0.02/$ wood product in electricity. The impacts from this electricity used to make wood products is part of the supply chain emissions for furniture. But industries making furniture also purchase electricity directly. Furthermore, each additional commodity that industries purchase also have electricity in the supply chain. If you scale all of this electricity based on one dollar output of furniture, you get the total requirement for electricity for furniture. In the 2016 summary level commodity model, this total requirement is $\$0.025 electricity/\$furniture$. This amount is multiplied by the direct emission factor for electricity for the same model, in kg CO_2 per dollar electricity.

$$\frac{\$0.025\ \text{electricity}}{\$\ \text{furniture}} * \frac{2.8\ \text{kg}\ CO_2}{\$\ \text{electricity}} \qquad [4]$$
$$= 0.07\ \text{kg}\ CO_2\ \text{emitted from electricity per dollar furniture}$$

But the supply chain CO_2 emissions do not just come from electricity. They come from the total requirements from all other commodities purchased in the supply chain, from which there are requirements from 69 of the 73 commodities in the model. Each of those total requirements is multiplied by its respective direct emission factor, as in the above, and then these amounts are summed to get the SEF in producer price, as in equation 3, of ~ .25 kg CO_2 emitted per dollar furniture.

2.4. Carbon Dioxide Equivalencies for Other Gases

For the major GHGs, CO_2, CH_4, N_2O, we report values in mass of the respective gas. But for the minor GHGs, for presentation purposes and for final factor reporting, we aggregate them as other gases, using the same 100-year GWP from the IPCC AR4 report as used in the latest release of the National Greenhouse Gas Inventory (EPA, 2020), to report them in CO_2 equivalents. These other gases include all minor GHGs present in the GHG Inventory.

2.5. Imports

Many of the commodities or industries present in the US are imported from overseas. These commodities or industry products are included in the USEEIO models used to calculate the factors, assuming that these products are manufactured like they are in the US. International transport emissions are not included in the margin emission factors.

2.6. Price Adjustments

While models represent industry transactions and emissions across various years, a common currency year is used for results reporting, controlling for the influence of inflation on model results. The most current year for which detailed industry output and chain-type price indices are available is used, which was 2018 at the time of report preparation. Ratios are derived for price adjustments using the BEA's detailed chain price indices that are published with the industry gross output data (BEA, 2019b). The direct and supply chain emission factors presented in this report are in 'producer price', and the IO tables used to build the models are the 'producer price' tables (see Table 1). The supply chain factors published in a separate file accompanying this report (Ingwersen and Li, 2020) are in 'purchaser price'. The purchaser price is most useful from a consumer perspective, and thus used for the reporting of final factors. We estimate the difference between producer and purchaser price using a combination of the Personal Consumption Expenditures and Private Investment in Equipment bridge tables (BEA, 2019b). More details on prices adjustments are presented in Appendix 1.

2.7. Data Quality Assessment

For each supply chain factors we calculate aggregate data quality scores for five data quality indicators from the EPA guidelines for data quality assessment (EPA, 2016) for data reliability, temporal correlation, geographic correlation, technological correlation, and data collection. Each indicator value varies from 1 (best quality) to 5 (worst quality). Scores are assigned to the GHG emissions by gas and industry in the National GHG Industry Attribution Model and propagated through the USEEIO model calculations. The methodology used for the score calculation is described in the model documentation (Yang et al., 2017).

3. Results

We describe the National GHG Industry Attribution model results, view industry economic output trends, and present direct emission factors as a context for describing the supply chain emission factors. We summarize the supply chain emission factors and analyze selected factors including their annual variation, primary contributors, differences in factors based on model variations, and summarize the results of SEF data quality assessment. We compare results for margin impact factors in relation to the supply chain factors. The National GHG Industry Attribution model is available separately (Yang et al., 2020). The complete set of supply chain factors at the BEA summary and detail levels for industry and commodity models in purchaser price are provided in a separate data file (Ingwersen and Li, 2020).

3.1. A Note on Result Presentation

The focus of our presentation in the main body of the report is on the summary level commodity emission factors and we mainly limit analysis to the primary GHGs — carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Household GHG emissions are presented in the context of national totals but otherwise the scope is limited to assessing industries. Sometimes BEA sector codes like *325* for chemical products are used in figures and tables for succinct identifiers. A common color scheme for sectors is used throughout the results to more easily identify them across figures. When multi-year results are not presented, we show the result for the most recent study year, 2016. *Wherever $ based results are presented in this report, it represents 2018 USD and in producer's value for comparability.* For certain analysis, we highlight results for 6 common manufactured commodities, machinery, computers and electronic products, furniture, food and beverages, paper products, and chemicals. We provide additional results for other models and commodities/industries in Appendices 5-9.

3.2. GHG Totals by Industry

National totals of each GHG by industry from 2010 to 2016 are shown in Figure 2, Figure 3, Figure 4, Figure 5, and Figure 6 at the BEA 'sector' level of sectoral aggregation.

National total CO_2 emissions decrease from 5658 million metric tons (MMT) in 2010 to 5244 MMT in 2016, except for a slight increase in 2013 and 2014 (Figure 2). The utilities sector is responsible for the largest amount of CO_2 emissions ranging from 29% to 33% of national totals, which is closely followed by the households sector which accounts for 21% to 23% of national total CO_2 emissions. The national CO_2 trend is not consistent across different sectors. For example, CO_2 emissions from utilities experience a decline in 2010-2012 that flattens from 2012-2014 and again declines from 2014-2016. Some sectors have higher CO_2 emissions in 2016 compared to 2010, like agriculture, information, educational services, transportation and warehousing, retail and wholesale, while arts, construction, and government have lower CO_2 in 2016 than in 2010. In general, there is annual fluctuation in these trends and no increases or decreases are steady across the study period. There are more pronounced changes for most sectors between 2011 and 2012 with decreases of ~10% for all groups except agriculture, and increases again in 2013 closer to 2011 levels. From 2014 to 2015, there are pronounced increases for wholesale, retail, and information that are tempered by decreases in 2015-2016.

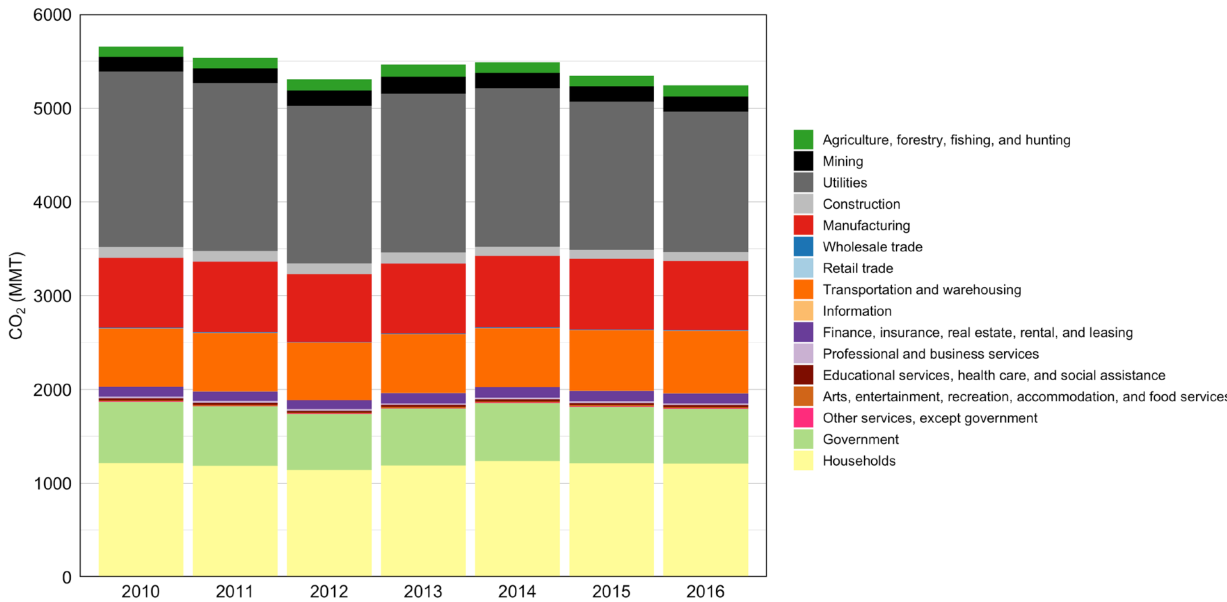


Figure 2: National level CO_2 trend by industries at sector level.

National total CH_4 emissions decrease from 28 MMT in 2010 to 26 MMT in 2016 (Figure 3). Agriculture and mining are the top two CH_4-emitting sectors: the former accounts for 36% to 38% while the latter accounts for 34% to 36% of national total CH_4 emissions. CH_4 reductions in professional and business services have the most influence on the total emissions reduction over the period, particularly in the 2010-2012 and then 2015-2016 periods. There are pronounced CH_4 decreases in years 2011-2012 and again from 2014 to 2015 for wholesale, retail, and information sectors that are erased in the succeeding years, but their contribution to national CH_4 emissions is negligible. Manufacturing CH_4 slightly increases over the period.

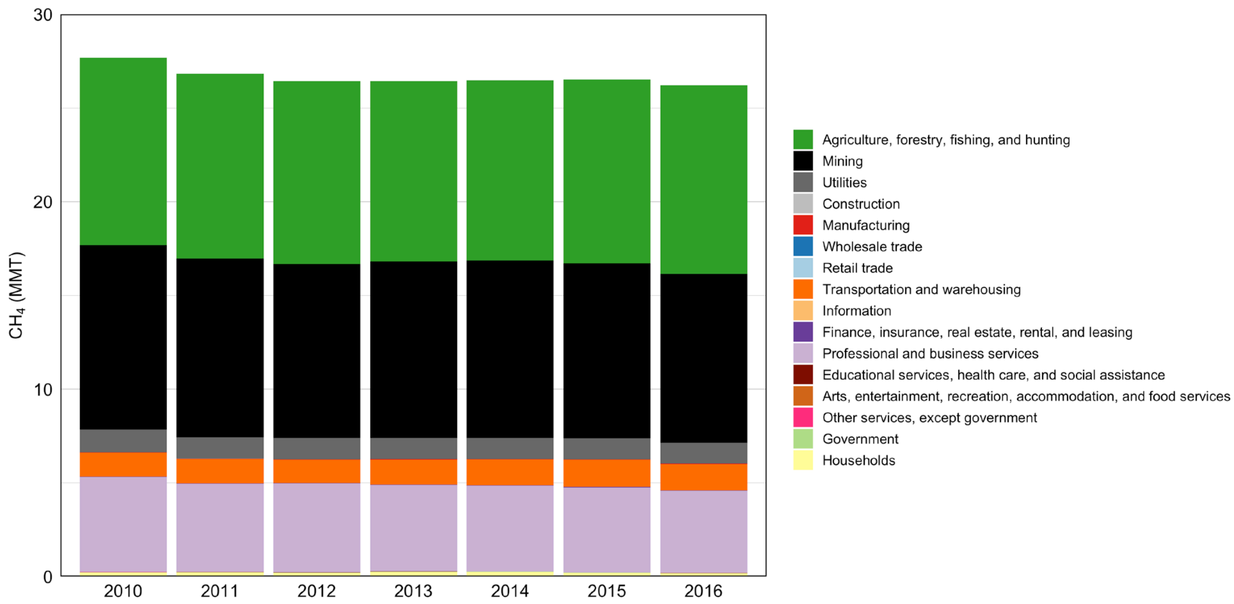


Figure 3: National level CH_4 trend by industries at sector level.

National total N_2O emissions decrease from 1.22 MMT in 2010 to 1.12 MMT in 2012 but increase thereafter with a peak value of 1.27 MMT in 2015 (Figure 4). Most of the N_2O emissions come from the agriculture, forestry, fishing, and hunting sector which is responsible for 79% to 83% of national totals. N_2O emissions are steady for most sectors, with the expectations of large relative increases in 2014-2015 for wholesale, retail, and information that are erased the following year. Overall decreases are seen in Construction and by households.

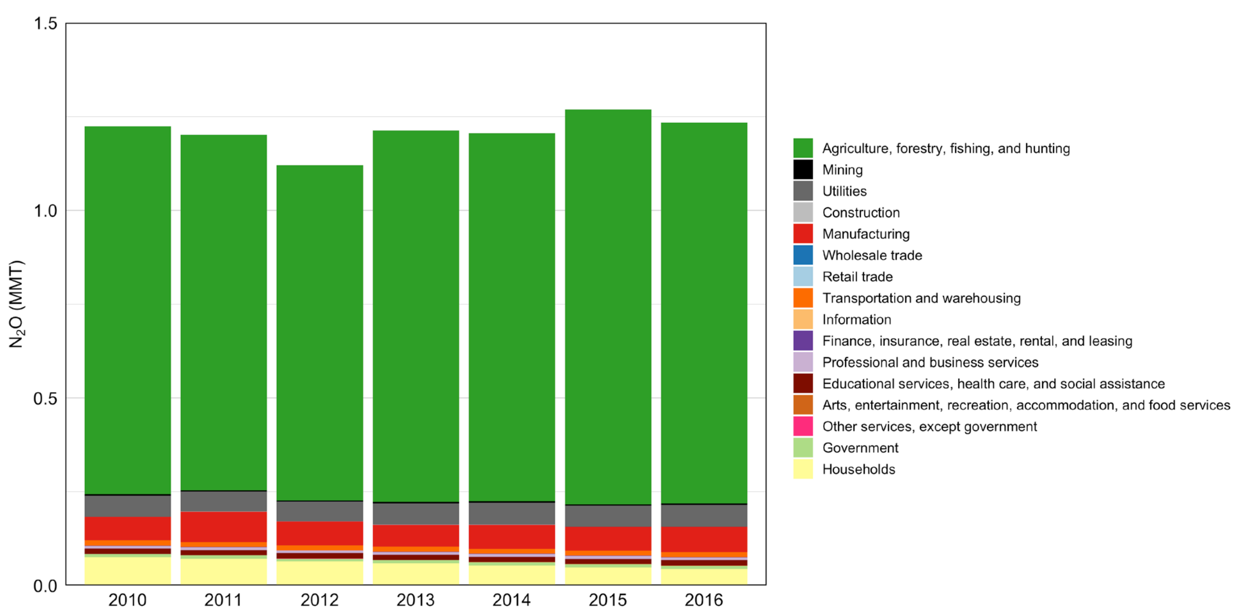


Figure 4: National level N_2O trend by industries at sector level.

National total emissions of other GHGs and their trends from 2010-2016 are shown in (Figure 5). Manufacturing is responsible for nearly all C2F6, C3F8, C4F8, CF4, HFC-23, and NF3 emissions: C2F6 emissions increase by 5%-30% during 2011-2013 compared to 1.64E-4 MMT in 2010 but decrease thereafter to 1.31E-4 MMT in 2016. C3F8 emissions almost double in 2011 from 1.12E-5 MMT in 2010 but decrease to 2010 level in the succeeding years. C4F8 emissions lack 2010 data but remain stable in 2011-2016. CF4 emissions drastically increase in 2011 (64% from 3.38E-4 MMT in 2010) then gradually decrease in the succeeding years to 3.25E-4 MMT in 2016. HFC-23 emissions increase in 2011 by 10% compared to 5.54E-4 MMT in 2010 then start decreasing until 2.09E-4 MMT in 2016, except for a slight increase in 2014-2015. NF3 emissions increase from 2.91E-4 MMT in 2010 to 4.07E-4 MMT in 2011 then decrease to 3.49E-4 MMT in 2012-2016, except for a slight dip in 2014.

All sectors, except for agriculture and utilities, contribute to national total HFC-125, HFC-134a, HFC-143a, HFC-236fa, and HFC-32 emissions. HFC-125 emissions from these sectors steadily increase from 2010-2016 and lead to HFC-125 national totals more than doubled from 2010 (6.95E-3 MMT) to 2016 (1.35E-2 MMT). Although HFC-134a emissions from some sectors like manufacturing and construction increase from 2010 (0.051 MMT) to 2016 (0.037 MMT), HFC-134a emissions from households significantly decrease over the period and lead to gradual decrease in national totals. National HFC-143a emissions increase from 2010 (4.13E-3 MMT) to 2016 (5.83E-3 MMT) due to notable increases in sectors like manufacturing, construction, and transportation and warehousing despite HFC-143a emissions from personal expenditure decrease over the period. National HFC-236fa emissions increase in 2012-2013 compared to 2010 (1.29E-4 MMT) but quickly drop below 2010 until 2016 (1.11E-4 MMT), mainly because HFC-236fa emissions from personal expenditure significantly decrease. HFC-32 emissions from all sectors except for agriculture and utilities steadily increase from 2010-2016 and lead to HFC-32 national totals more than tripled from 2010 (2.41E-3 MMT) to 2016 (7.51E-3 MMT). SF6 emissions only come from utilities and manufacturing. In both sectors, SF6 emissions slightly increase in 2011 then decrease thereafter and hit the lowest level in 2015. As a result, SF6 national totals increase from 2010 (3.68E-4 MMT) to 2011 (4.04E-4 MMT) then decrease to 2.59E-4 MMT in 2015 and 2.68E-4 MMT in 2016.

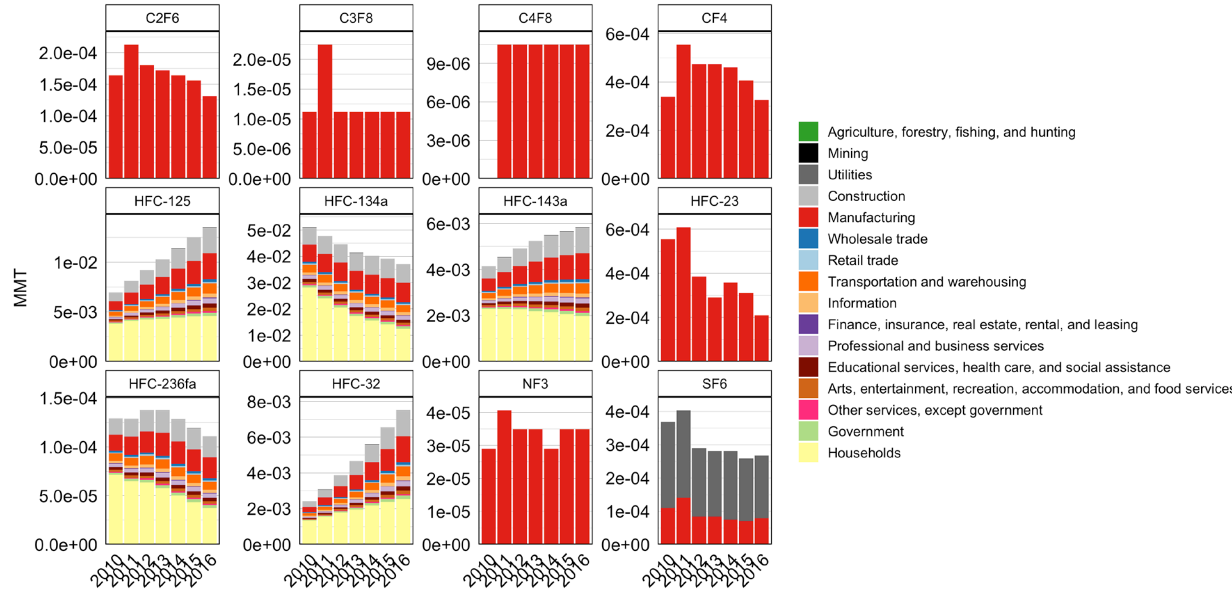


Figure 5: National level other GHGs trend by industries at sector level.

National totals of these 'other' GHGs, when combined using CO_2 equivalents, increase from 2010 (140 MMT CO_2e) to 2016 (146 MMT CO_2e) (Figure 6). Among all sectors, utilities and households are the only two that have decreasing totals of other GHGs: 5.9 to 4.3 MMT CO_2e and 65 to 47 MMT CO_2e over the period, respectively. All the other sectors have steadily increasing totals of other GHGs.

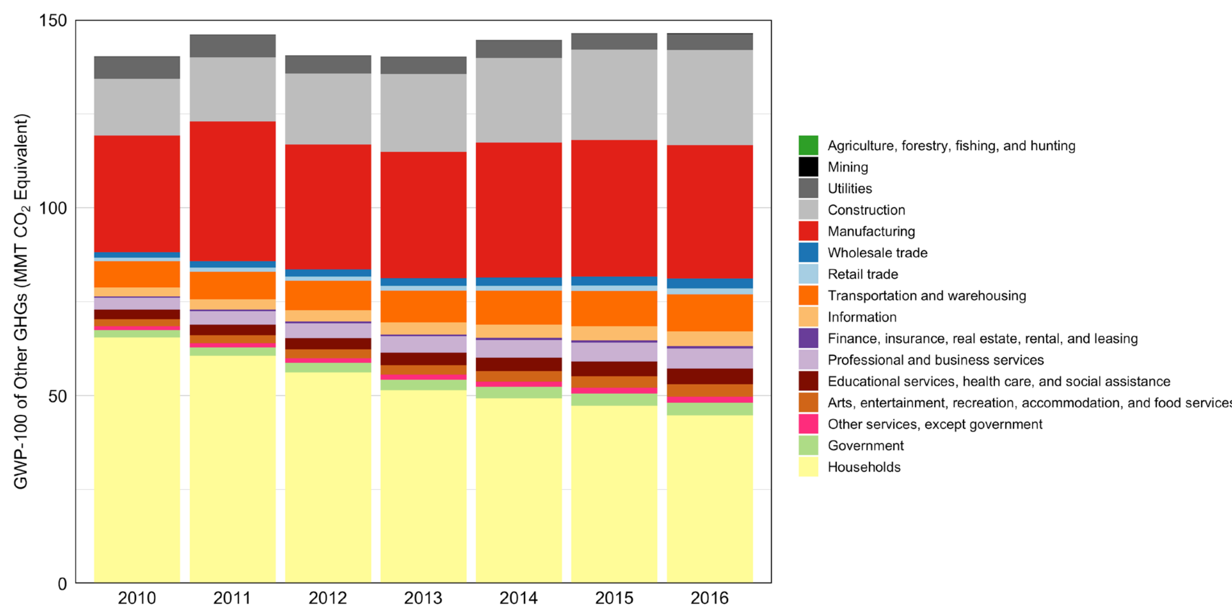


Figure 6: National level GWP-100 of other GHGs trend by industries at sector level.

The top ten industries at the ‘summary’ level of aggregation (73 in total) by direct CO_2, CH_4, and N_2O emissions are shown in Table 1, Table 2, and Table 3, respectively. The industries are ranked by their direct emissions in the year of 2016.

Utilities have the largest amount of direct CO_2 emissions due to combustion of fossil fuels in electric power generation (Table 1). Direct CO_2 emissions from utilities decrease from 1874 MMT in 2010 to 1678 in 2012 but slightly increase to 1692 MMT in 2013 then decline to 1502 MMT in 2016. Truck transportation industry ranks 2nd and has a steady increasing trend in direct CO_2 emissions from 2010 (342 MMT) to 2016 (373 MMT) except for a slight dip in 2012. Another transportation industry in the top 10 list is air transportation which ranks 6th and has more direct CO_2 emissions in 2016 than in 2010 despite a minor decline in 2011-2012. State and local government enterprises ranks 3rd and has declining direct CO_2 emissions from 2010 to 2016, while state and local general government ranks 5th and has a bumpy trend from 2010 to 2016. Manufacturing industries including chemical products, petroleum and coal products, and nonmetallic mineral products ranks 4th, 7th, and 10th in the list, respectively: direct CO_2 emissions from chemical products slightly decrease in 2011-2012 (~1 MMT) but dramatically increase in the succeeding years; direct CO_2 emissions from petroleum and coal products overall decline from 2010 to 2016 with a few rises and drops over the period; and direct CO_2 emissions from nonmetallic mineral products increase from 2010 to 2014 then decline slightly through 2016. Farms ranks 8th in the list and has slightly increasing direct CO_2 emissions from 2010 to 2016 except for a decrease in 2014-2015. Construction ranks 10th in the list and has increasing direct CO_2 emissions from 2010 (112 MMT) to 2013 (120 MMT) but decreasing emissions in the succeeding years (95 MMT in 2016).

Table 1: Top 10 industries by direct CO_2 emission totals at 'summary' level. Unit is million metric tons (MMT).

Sector Code	Sector Name	2010	2011	2012	2013	2014	2015	2016
22	Utilities	1874.31	1790.81	1678.42	1691.71	1691.55	1577.69	1501.88
484	Truck transportation	342.38	347.40	345.52	350.47	361.03	370.41	373.43
GSLE	State and local government enterprises	363.89	350.76	331.57	334.55	335.98	318.46	306.06
325	Chemical products	191.32	190.53	189.43	193.61	280.56	283.04	274.53
GSLG	State and local general government	199.21	194.73	184.74	191.54	198.52	206.29	203.24
324	Petroleum and coal products	216.53	217.47	192.04	208.09	157.47	158.18	156.04
481	Air transportation	142.67	138.10	134.89	138.15	139.37	147.95	155.57
111CA	Farms	104.08	107.09	116.55	124.04	109.56	107.68	113.00
23	Construction	112.41	113.02	114.44	119.91	96.42	95.18	94.95
327	Nonmetallic mineral products	82.68	83.86	86.54	88.16	96.34	95.91	94.74

Farms have the largest amount of direct CH_4 emissions which decrease by ~300 thousand metric tons (kMT) from 2010 to 2014 but show a pronounced increase of ~400 kMT from 2014 to 2016 (Table 2). Oil and gas extraction industry ranks 2nd and has a bumpy trend in direct CH_4 emissions from 2010 to 2016. Another heavy industry in the top 10 list is mining, except oil and gas which ranks 4th and has a steady declining trend in direct CH_4 emissions from 2010 to 2016. Direct CH_4 from the mining industries can be attributed to gas leakage in mining processes. Waste management and remediation services ranks 3rd and has a steady declining trend of direct CH_4 emissions from 2010 to 2016 except for a slight increase in 2012. Transportation industries including pipeline transportation, other transportation and support activities, water transportation, and transit and ground passenger transportation rank 5th, 7th, 9th, and 10th in the list, respectively: direct CH_4 emissions from pipeline transportation increase from 2010 to 2016 except for a slight decrease in 2012; direct CH_4 emissions from other transportation and support activities overall decline from 2010 to 2016; direct CH_4 emissions from water transportation remain the same from 2010-2014 then decrease in 2015-2016; and direct CH_4 emissions from transit and ground passenger transportation decline from 2010 to 2016. Utilities and chemical products rank 6th and 8th in the list, respectively. Direct CH_4 emissions from utilities decline from 2010 to 2016, while direct CH_4 emissions from chemical products increase from 2010 to 2016.

Table 2: Top 10 industries by direct CH_4 emission totals at 'summary' level. Unit is thousand metric tons (kMT).

Sector Code	Sector Name	2010	2011	2012	2013	2014	2015	2016
111CA	Farms	9992.02	9857.00	9759.99	9624.11	9609.63	9821.95	10076.65
211	Oil and gas extraction	6267.76	6406.81	6354.84	6578.88	6625.65	6620.83	6580.69
562	Waste management and remediation services	5064.16	4712.16	4756.10	4612.16	4592.10	4552.16	4392.16
212	Mining, except oil and gas	3575.28	3120.31	2923.68	2847.87	2849.74	2714.71	2430.47
486	Pipeline transportation	1148.00	1172.00	1124.00	1236.00	1292.00	1364.00	1312.00
22	Utilities	1209.23	1149.23	1136.54	1121.23	1121.22	1120.55	1108.55
487OS	Other transportation and support activities	90.82	82.59	71.62	66.14	56.89	55.16	55.16
325	Chemical products	6.39	6.41	7.24	7.65	9.62	12.57	14.81
483	Water transportation	16.00	16.00	16.00	16.00	12.00	12.00	12.00
485	Transit and ground passenger transportation	15.65	14.11	12.05	11.02	9.75	8.96	8.96

Farms have more than 90% of the total share of direct N_2O emissions. They increase slightly over the period relative to 2010 values from ~980 kMT in 2010 to ~1015 kMT in 2016 (Table 3). Chemical products, ranking 2nd, and utilities, ranking 3rd, both have bumpy trends in direct N_2O emissions from 2010-2016. Direct N_2O emissions from ambulatory health care services and hospitals, ranking 4th and 7th, both remain the same from 2010-2016 at ~8 kMT and ~6 kMT, respectively. Waste management and remediation services ranks 5th showing slight increases in direct N_2O emissions over the period. State and local government enterprises rank 6th and have relatively stable direct N_2O emissions from 2010-2016. Transportation industries including air transportation, truck transportation, and other transportation and support activities rank 8th, 9th, and 10th in the list, respectively.

Table 3: Top 10 industries by direct N_2O emission totals at 'summary' level. Unit is thousand metric tons (kMT).

Sector Code	Sector Name	2010	2011	2012	2013	2014	2015	2016
111CA	Farms	980.76	947.18	893.48	990.47	981.12	1052.86	1014.97
325	Chemical products	60.33	78.14	61.05	56.34	62.17	60.69	65.09
22	Utilities	56.02	53.24	51.91	56.42	57.87	55.92	58.26
621	Ambulatory health care services	8.27	8.27	8.27	8.27	8.27	8.27	8.27
562	Waste management and remediation services	6.38	6.72	6.72	7.05	7.39	7.39	7.39
GSLE	State and local government enterprises	6.87	6.40	6.12	6.82	7.01	6.68	6.96
622	Hospitals	5.88	5.88	5.88	5.88	5.88	5.89	5.88
481	Air transportation	4.70	4.70	4.36	4.70	4.70	5.03	5.03
484	Truck transportation	4.36	3.69	3.69	3.36	3.02	3.02	2.68
487OS	Other transportation and support activities	2.30	2.30	2.30	2.30	2.30	2.53	2.53

3.3. Economic Output by Industry

We do not calculate original values for economic output in this study, but understanding industry gross output trends are essential for explaining direct and supply chain emission factors, and therefore we summarize these trends. Trends of industry gross output by sector from 2010 to 2016 are shown in Figure 7. National industry gross output increased from 29 trillion in 2010 to 33.6 trillion dollars in 2016. Industries including manufacturing, retail, information, finance, professional services, arts, and educational services, health care, and social assistance have steady economic growth from 2010-2016. Gross output from utilities decreased in 2010-2012 but increased in 2013-2015 then dropped again in 2016 to 0.50 trillion dollars, below the 2010 level of 0.52 trillion dollars.

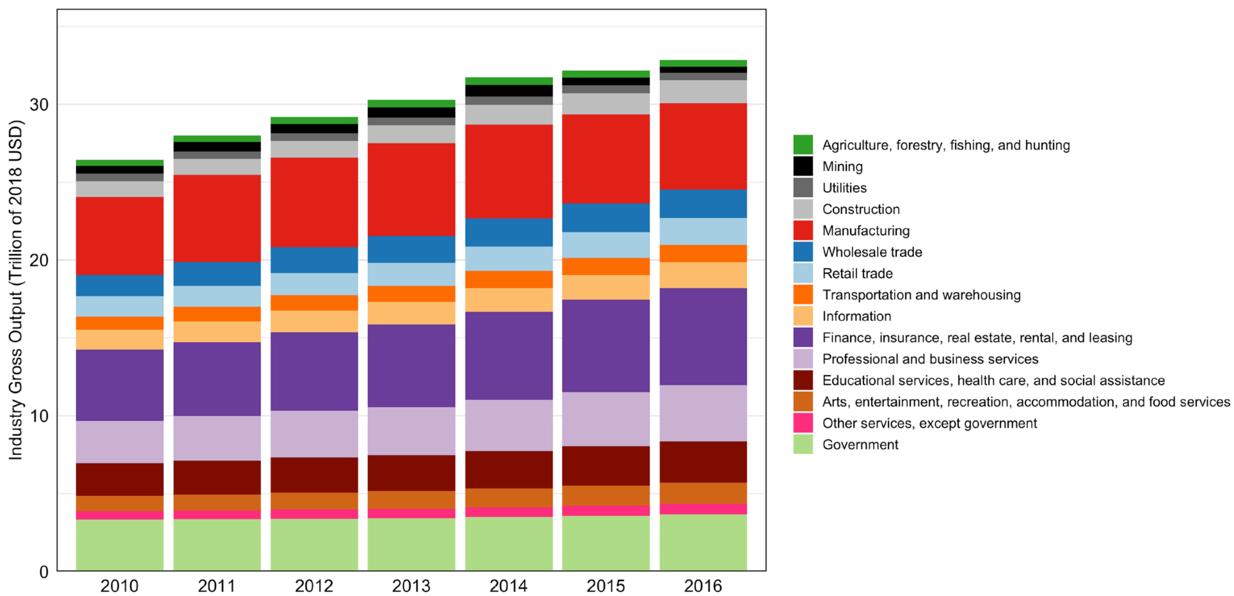


Figure 7: Industry gross output by BEA sector.

3.4. Direct Emission Factors

The top 10 'summary' level commodities by direct CO_2, CH_4, and N_2O emission factors (DEFs) in 2016 are shown in Table 4, Table 5, and Table 6, respectively.

Utilities (22) have the largest direct CO_2 factor of 2.81 kg/$ among all 73 'summary' level commodities (Table 4). Major transportation sectors including truck transportation (484), pipeline transportation (486), air transportation (481), and rail transportation (482) are also in the list, ranking 2nd, 3rd, 6th, and 9th, respectively. State and local government enterprises (GSLE) and federal government enterprises (GFE) have direct CO_2 factor of 1.0 kg/$ and 0.68 kg/$, ranking 4th and 7th, respectively. Nonmetallic mineral products (327) is the only manufacturing sector in the top 10 list, ranking 6th and having direct CO_2 factor of 0.80 kg/$. Mining, except oil and gas (212) is the only mining sector in the top 10 list, ranking 8th and having direct CO_2 factor of 0.67 kg/$. Oil and gas extraction (211) ranks 10th and has direct CO_2 factor of 0.58 kg/$.

Table 4: Top 10 direct CO_2 emission factors for commodities at 'summary' level in 2016.

Sector Code	Sector Name	Direct Emission Factor (kg/$)
22	Utilities	2.81
484	Truck transportation	1.22
486	Pipeline transportation	1.07
GSLE	State and local government enterprises	1.01
327	Nonmetallic mineral products	0.80
481	Air transportation	0.77
GFE	Federal government enterprises	0.68
212	Mining, except oil and gas	0.67
482	Rail transportation	0.63
211	Oil and gas extraction	0.58

Waste management and remediation services (562) have the largest direct CH_4 factor of ~42 g/$ among all 73 'summary' level commodities (Table 5). Mining sectors including oil and gas extraction (211), mining, except oil and gas (212), and support activities for mining (213) have direct CH_4 factor of ~41 g/$, ~29 g/$, and ~12 g/$, and ranking 2nd, 3rd, and 6th, respectively. Pipeline transportation (486) ranks 4th and has direct CH_4 factor of ~29 g/$, while farms (111CA) ranks 5th and has direct CH_4 factor of ~28 g/$. Scrap, used and secondhand goods (Used), forestry, fishing, and related activities (111FF), utilities (22), and petroleum and coal products (324) have direct CH_4 factor smaller than 4 g/$ and rank 7th-10th in the list, respectively.

Table 5: Top 10 direct CH_4 emission factors for commodities at 'summary' level in 2016.

Sector Code	Sector Name	Direct Emission Factor (g/$)
562	Waste management and remediation services	42.41
211	Oil and gas extraction	40.98
212	Mining, except oil and gas	29.39
486	Pipeline transportation	29.25
111CA	Farms	27.59
213	Support activities for mining	12.47
Used	Scrap, used and secondhand goods	3.56
113FF	Forestry, fishing, and related activities	2.01
22	Utilities	1.92
324	Petroleum and coal products	1.37

Farms (111CA) have the largest direct N_2O factor of ~2.8 g/$ among all 73 'summary' level commodities, followed by another agricultural sector forestry, fishing, and related activities (113FF) which has direct N_2O factor of 0.2 g/$ (Table 6). Utilities (22) and chemical products (325) have direct N_2O factor of ~0.1 g/$, ranking 3rd and 4th, followed by waste management and remediation services (562) which has the factor of ~0.07 g/$ and ranks 5th. Amusements, gambling, and recreation industries (713) and water transportation (483) have the direct N_2O factor of ~0.04 g/$ and rank 6th and 7th in the list. Air transportation (481) ranks 8th and has direct N_2O factor of ~0.03 g/$. State and local government enterprises (GSLE), and mining, except oil and gas (212) have the same direct N_2O factors of ~0.02 g/$ and round out top 10 2016 summary commodity direct N_2O factors.

Table 6: Top 10 direct N_2O emission factors for commodities at 'summary' level in 2016.

Sector Code	Sector Name	Direct Emission Factor (g/$)
111CA	Farms	2.78
113FF	Forestry, fishing, and related activities	0.20
22	Utilities	0.11
325	Chemical products	0.09
562	Waste management and remediation services	0.07
713	Amusements, gambling, and recreation industries	0.04
483	Water transportation	0.04
481	Air transportation	0.03
GSLE	State and local government enterprises	0.02
212	Mining, except oil and gas	0.02

3.4.1. Direct Emissions vs. Output Contributions to Direct Emission Factors

The direct emissions factors can be interpreted as a relationship between direct emissions from production of an industry and output from the industry (see the definition of direct emission factors in Table 1). We select three 'summary' level industries to show their gross output and direct CO_2, CH_4, and N_2O emission trends from 2010-2016 (Figure 8): farms (111CA), utilities (22), and truck transportation (484). Appendix 5 contains the same figures for all industries at summary and detail levels.

National gross output from farms (111CA) increases from 2010 (340 billion dollars) to 2016 (385 billion dollars) except for a slight dip in 2011-2012. Direct CO_2 emissions (red line) from farms increase from 2010 (104 MMT) to 2013 (124 MMT) then decline in 2014-2015 before rising again in 2016 (113 MMT). Direct CH_4 emissions (blue line) from farms decrease from 2010 (10 MMT) to 2014 (9.6 MMT) then increase thereafter until 2016 (10.1 MMT). Direct N_2O emissions (green line) from farms have an overall increasing but bumpy trend from 2010-2016: they decrease from 981 kMT in 2010 to 893 kMT in 2012, rise to 990 kMT in 2013; after a slight decline in 2014, they increase to 1053 kMT in 2015 then decrease to 1015 kMT in 2016.

National gross output from utilities (22) decreases from 2010 (516 billion dollars) to 2016 (498 billion dollars) except for a pronounced growth period in 2013-2015. Direct CO_2 emissions (red line) from utilities overall decrease from 2010 (1874 MMT) to 2016 (1502 MMT), even during economic growth years for this industry (2013-2015) in which the emissions decrease from 1692 MMT 2013 to 1578 MMT in 2015. Direct CH_4 emissions (blue line) from utilities steadily decrease from 2010 (1.2 MMT) to 2016 (1.1 MMT). Direct N_2O emissions (green line) from utilities have an overall increasing but bumpy trend from 2010-2016: they decrease from 56 kMT in 2010 to 52 kMT in 2012 then rise to 58 kMT in 2014; after a slight decline in 2015, they increase to 58 kMT in 2016.

National gross output from truck transportation (484) steadily increases from 282 billion dollars in 2010 to 338 billion dollars in 2015 then slightly decreases to 334 billion dollars in 2016. Similar to the national gross output, direct CO_2 emissions (red line) from truck transportation have a steady increasing trend from 2010 (342 kMT) to 2016 (373 kMT) except for a small dip in 2012. Direct CH_4 emissions (blue line) from truck transportation steadily decrease from 2010 (4 kMT) to 2016 (0 kMT). Direct N_2O emissions (green line) from truck transportation gradually decrease from 4 kMT in 2010 to 3 kMT in 2016.

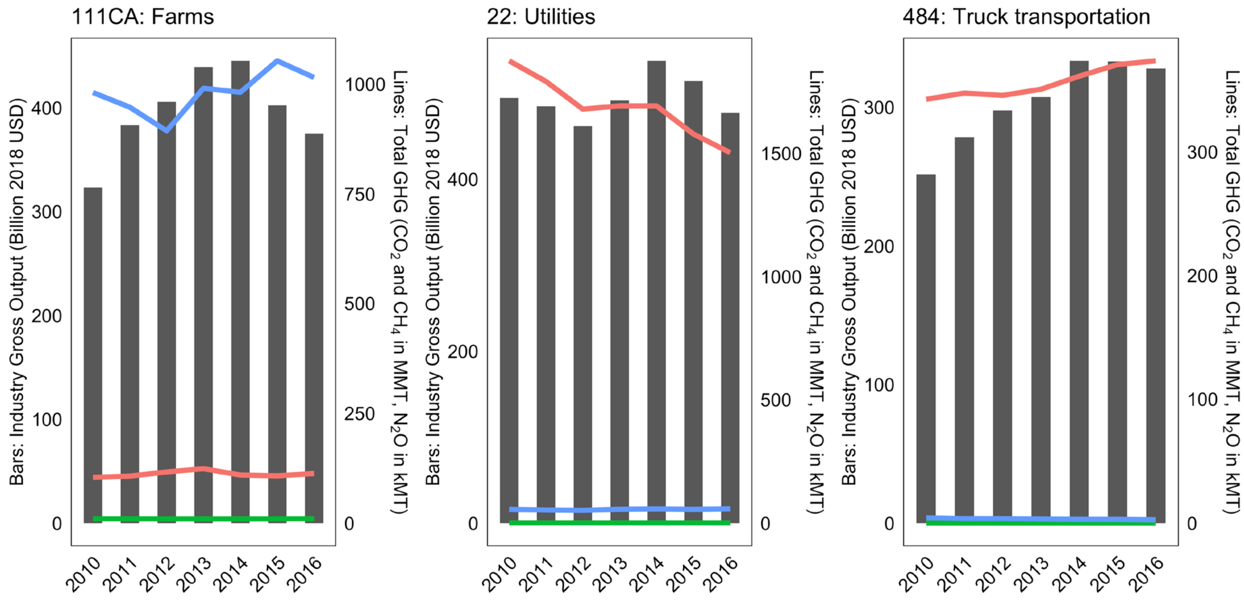


Figure 8: National level gross output and direct emission trends for selected industries at summary level. Red line is CO_2. Blue line is CH_4. Green line is N_2O.

3.5. Supply Chain Emission Factors

Supply chain CO_2, CH_4, and N_2O emission factors (SEFs) by 'summary' level commodities are shown in Figure 9, Figure 10, and Figure 11, respectively. Appendix 6 has tables of annual percent change in SEFs for all commodities and industries at the summary and detail levels. Appendix 6 has tables of annual percent change in SEFs for all commodities and industries at the summary and detail levels.

As mentioned above, the values in tables in this report are in producer prices, which reduce the uncertainty associated with the margins, but on the other hand are less appropriate for use with spend data as they are commonly used for Scope 3 GHG emissions accounting. Supply chain emission factors in the associated data file are in purchaser prices (Ingwersen and Li, 2020).

For supply chain CO_2 factors (Figure 9) at the summary level, commodities from all sectors have lower factors in 2016 than in 2012, except for 6 commodities sectors including farms (111CA), oil and gas extraction (211), mining, except oil and gas (212), support activities for mining (213), petroleum and coal products (324), and motion picture and sound recording industries (512). More than 2/3 of commodities have the lowest factors in 2016. Supply chain CO_2 factors are relatively low for commodities from the service sectors (light blue, light green, brown, dark purple, light purple, and light red). Utilities (dark grey) have the largest SEF among all 'summary' level commodities: ranging from 3.1 to 3.8 kg/$ in 2012-2016 and have a decreasing trend from 2012 to 2015 followed by a slight increase in 2016 to a level below 2012. Nonmetallic mineral products (dark red), truck transportation (dark blue), pipeline transportation (dark blue), and state and local government enterprises (pink) have the second largest supply chain CO_2 factors. The factor decreases from 2012 to 2016 for all four of these commodities, except for truck transportation (dark blue), in which the factor decreases from 2012 to 2014 but increases in 2015-2016 not quite reaching its 2012 value. The CO_2 SEF of petroleum and coal products (dark red) significantly increases from 0.5 kg/$ in 2012 to 1.2 kg/$ in 2016, which is the largest deviation (0.7 kg/$) among all commodities.

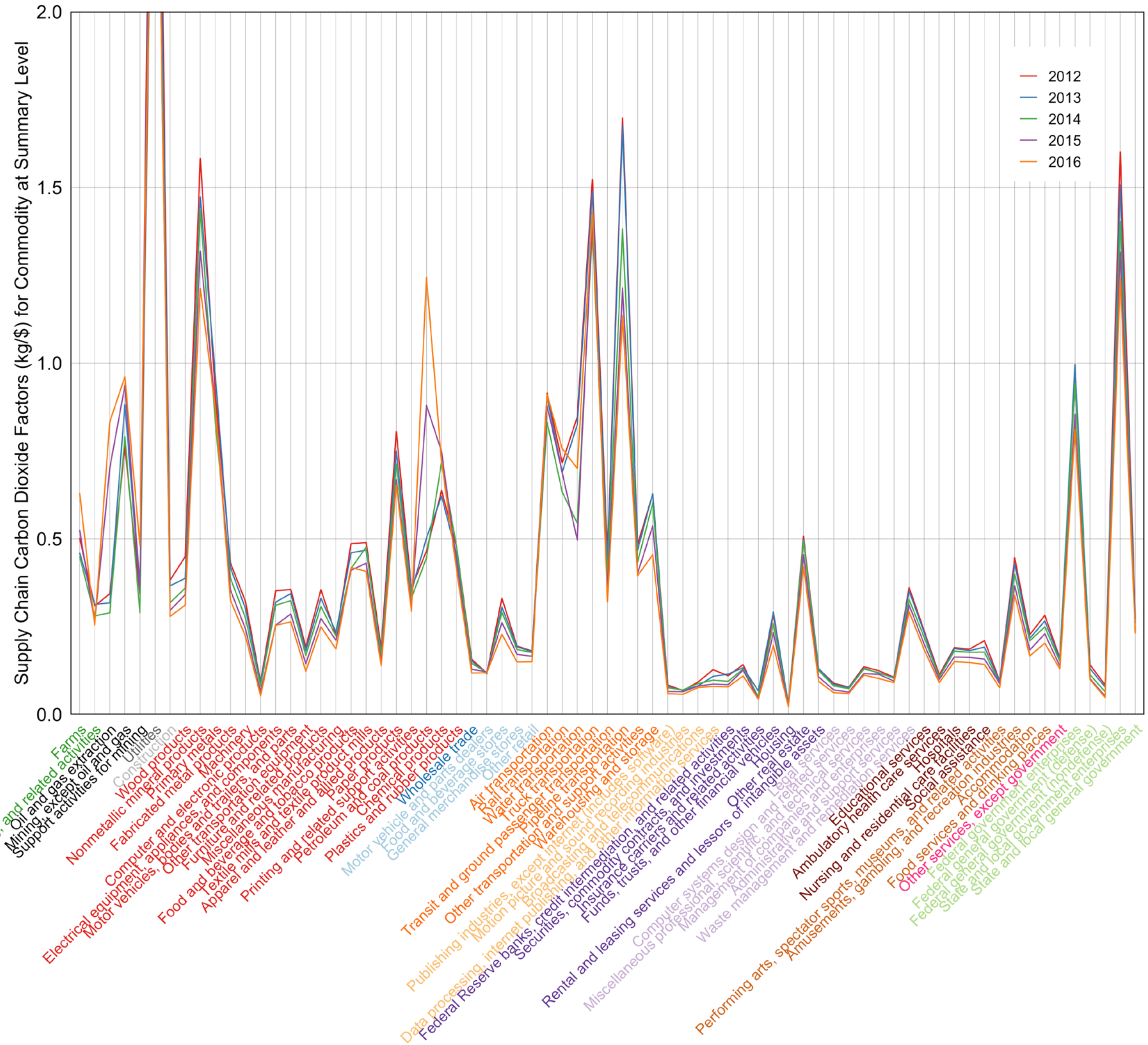


Figure 9: Supply chain CO_2 emission factors for commodities at summary level.

For supply chain CH_4 factors (Figure 10) at the summary level, all commodities have lower factors in 2016 than in 2012, except for oil and gas extraction (211), support activities for mining (213), and petroleum and coal products (324). 61 of 73 sectors have the lowest factors in 2016. Waste management and remediation services (brown) has the largest factor among all 'summary' level commodities which decreases from 61 g/$ in 2012 to 46 g/$ in 2016. Farms (dark green), oil and gas extraction (black), mining, except oil and gas (black), petroleum and coal products (dark red), and pipeline transportation (dark blue) have the second largest supply chain CH_4 factors, ranging from 10 to 45 g/$. The factor increases from 2012 to 2016 for all five commodities, except for pipeline transportation (dark blue). The CH_4 SEF of oil and gas extraction (black) slightly decreased from 2012 to 2014 then significantly increases to ~40 g/$ in 2016, which creates the largest change over the period among all commodities.

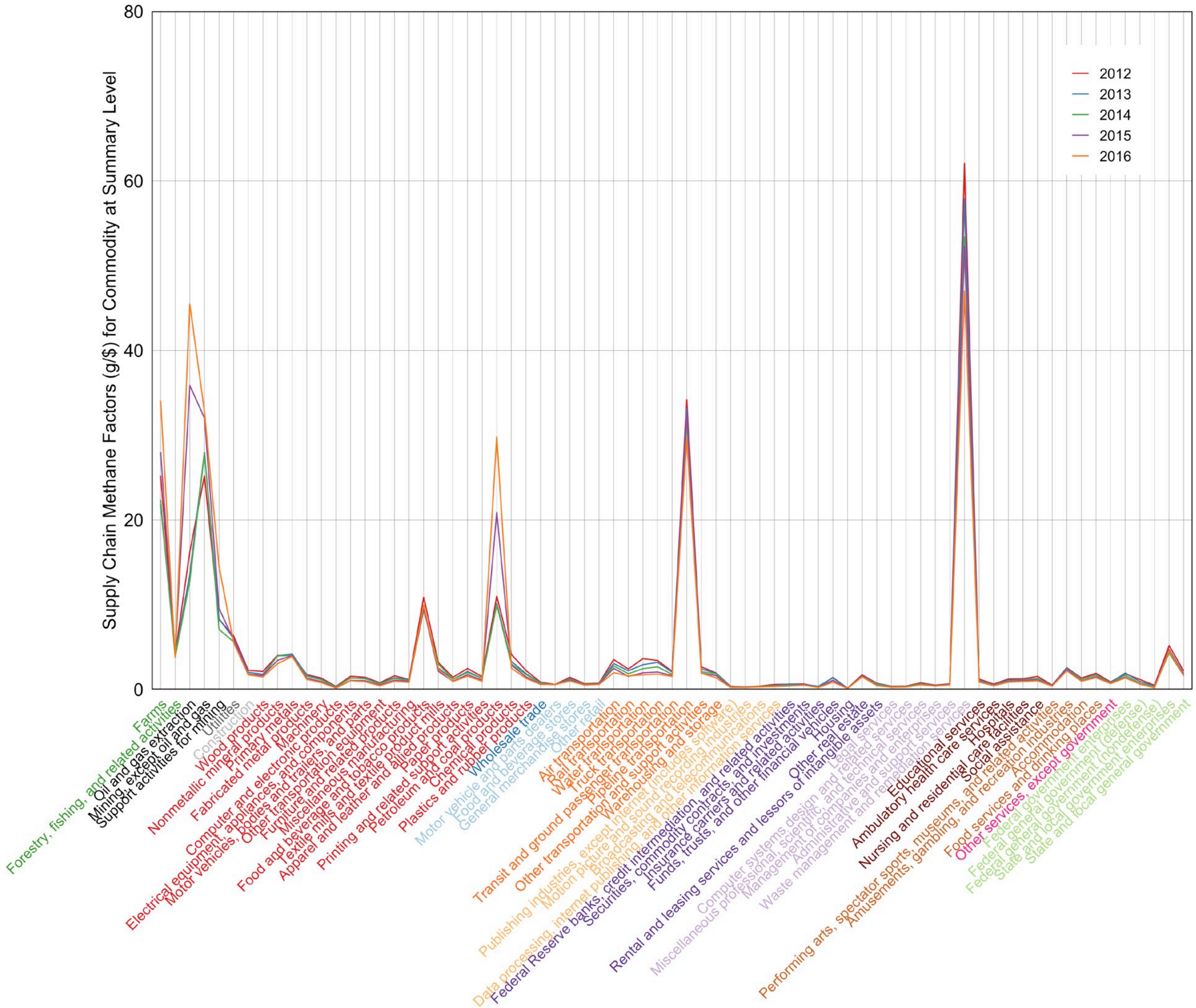


Figure 10: Supply chain CH_4 emission factors for commodities at summary level.

For supply chain N_2O factors (Figure 11), all commodities have lower factors in 2016 than in 2012, except for 16 commodities including farms (111CA), forestry, fishing, and related activities (113FF), oil and gas extraction (211), mining, except oil and gas (212), support activities for mining (213), utilities (22), food and beverage and tobacco products (311FT), petroleum and coal products (324), primary metals (331), motor vehicles and parts dealers (441), rail transportation (482), administrative and support services (561), amusements, gambling, and recreation industries (713), state and local general government (GSLG), other real estate (ORE), and scrap, used and secondhand goods (USED). 45 of 73 commodities have the lowest SEFs in 2016. Farms (dark green) has the largest factor among all ‘summary’ level commodities. Farms’ SEF decreases from 2.22 g/$ in 2012 to 2.16 g/$ in 2013 then increases to 3.31 g/$ in 2016, which creates the largest deviation (1.17 g/$) among all sectors. The SEF for food and beverage and tobacco products (dark red) decreases from 0.89 g/$ in 2012 to 0.87 g/$ in 2014 then increases to 0.94 g/$ in 2015 and decreases slightly to 0.94 g/$ in 2016. The SEFs for other commodities other than farms (dark green) and food (dark red) are smaller than 0.4 g/$ throughout the five-year range.

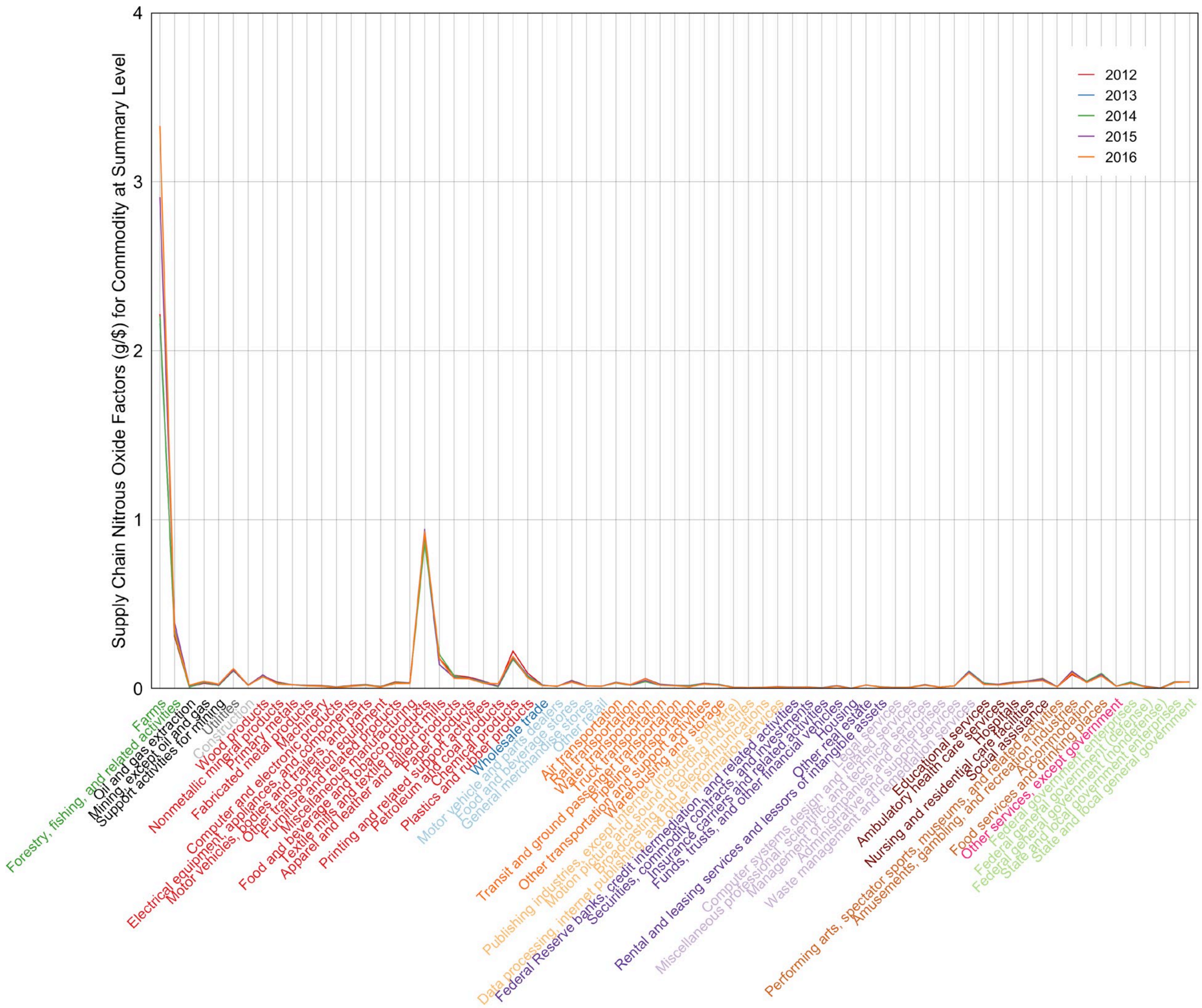


Figure 11: Supply chain N2O emission factors for commodities at summary level.

Top 10 'summary' level commodities by supply chain CO_2, CH_4, and N_2O emission factors in 2016 are shown in Table 7, Table 8, and Table 9, respectively. Supply chain emission factors are slightly larger than direct emission factors as emissions from supply chain are included in the metric.

Utilities (22) has the largest supply chain CO_2 factor of 3.11 kg/$ among all 73 'summary' level commodities. Three transportation commodities including truck (484), pipeline (486), and air transportation (481) have supply chain CO_2 factors of 1.43 kg/$, 1.13 kg/$, and 0.91 kg/$ and rank 2nd, 6th, and 8th in the list, respectively. Manufactured commodities including petroleum and coal products (324), nonmetallic mineral products (327), and primary metals (331) are in the top 10 list, having supply chain CO_2 factor of 1.24 kg/$, 1.21 kg/$, and 0.91 kg/$ and ranking

3rd, 5th, and 9th, respectively. State and local government enterprises (GSLE) has supply chain CO_2 factor of 1.24 kg/$ and rank 4th in the list. Mining sectors including mining, except oil and gas (212) and oil and gas extraction (211) have supply chain CO_2 factor of 0.96 kg/$ and 0.83 kg/$, ranking 7th and 10th, respectively.

Waste management and remediation services (562) have the largest supply chain CH_4 factor of 46.11 g/$ among all 73 ‘summary’ level commodities. Mining commodities including oil and gas extraction (211), mining, except oil and gas (212), and support activities for mining (213) have supply chain CH_4 factors of 45.43 g/$, 32.81 g/$, and 14.49 g/$, and rank 2nd (same with DEF), 4th (same with DEF), and 7th (not in DEF top 10 list), respectively. Farms (111CA) ranks 3rd (was 1st in direct emission factor top 10 list) and has supply chain CH_4 factor of 34.08 g/$, followed by petroleum and coal products (324), ranking 5th with a factor of 29.81 g/$, and pipeline transportation (486), ranking 6th (was 2nd in direct emission factor top 10 list) with a factor of 29.59 g/$. Food and beverage and tobacco products (311FT), utilities (22), and scrap, used and secondhand goods (Used) have smaller CH_4 SEFs than 10 g/$ and rank 8th-10th in the list, respectively.

Farms (111CA) have the largest supply chain N_2O factor of 3.33 g/$ among all 73 ‘summary’ level commodities (was also the largest in direct emission factor). Another agricultural commodity forestry, fishing, and related activities (113FF) ranks 3rd and has supply chain N_2O factor of 0.34 g/$. Five manufactured commodities including food and beverage and tobacco products (311FT, ranking 2nd), chemical products (325, ranking 4th), textile mills and textile product mills (313TT, ranking 5th), wood products (321, ranking 9th), and plastics and rubber products (326, ranking 10th) are in the top 10 list, which have supply chain N_2O factors of 0.93 g/$, 0.20 g/$, 0.18 g/$, 0.07 g/$, and 0.07 g/$, respectively. Utilities (22) have supply chain N_2O factors of 0.12 g/$ and rank 6th in the list. Amusements, gambling, and recreation industries (713) and food services and drinking places (722) have N_2O SEFs that are close: 0.09 g/$ and 0.07 g/$, and rank 7th and 8th in the list, respectively.

Table 7: Top 10 supply chain CO_2 emission factors for commodities at 'summary' level in 2016.

Sector Code	Sector Name	Supply Chain Emission Factor (kg/$)
22	Utilities	3.11
484	Truck transportation	1.43
324	Petroleum and coal products	1.24
GSLE	State and local government enterprises	1.24
327	Nonmetallic mineral products	1.21
486	Pipeline transportation	1.13
212	Mining, except oil and gas	0.96
481	Air transportation	0.91
331	Primary metals	0.87
211	Oil and gas extraction	0.83

Table 8: Top 10 supply chain CH_4 emission factors for commodities at 'summary' level in 2016.

Sector Code	Sector Name	Supply Chain Emission Factor (g/$)
562	Waste management and remediation services	47.00
211	Oil and gas extraction	45.43
111CA	Farms	34.07
212	Mining, except oil and gas	32.80
324	Petroleum and coal products	29.80
486	Pipeline transportation	29.59
213	Support activities for mining	14.49
311FT	Food and beverage and tobacco products	9.99
22	Utilities	5.51
Used	Scrap, used and secondhand goods	5.43

Table 9: Top 10 supply chain N_2O emission factors for commodities at 'summary' level in 2016.

Sector Code	Sector Name	Supply Chain Emission Factor (g/$)
111CA	Farms	3.33
311FT	Food and beverage and tobacco products	0.93
113FF	Forestry, fishing, and related activities	0.34
325	Chemical products	0.19
313TT	Textile mills and textile product mills	0.18
22	Utilities	0.12
562	Waste management and remediation services	0.09
713	Amusements, gambling, and recreation industries	0.09
722	Food services and drinking places	0.08
321	Wood products	0.07

3.5.1. Direct vs. Indirect Sources of Supply Chain Emissions

We demonstrate how much of the emissions embedded within 1 dollar of commodity output comes from direct production for 2016 summary level commodities in Figure 12, Figure 13, and Figure 14.

For about half of US commodities, less than 20% of their supply chain CO_2 emissions are from direct emissions (Figure 12). Direct emissions make up ~50% for agriculture (dark green), 68%-70% for mining (black), 90% for utilities (dark grey), and 28% for construction (light grey).

Most manufactured commodities (dark red) have less than 20% direct emissions, except for nonmetallic mineral products (66%), chemical products (54%), petroleum and coal products (44%), primary metals (41%), paper products (40%), and printing and related support activities (27%). Direct emissions are only 7% for wholesale trade (dark orange) and 2%-12% for retail trade (light orange). Direct emissions make up larger than 50% of emissions for transportation commodities, in which pipeline transportation has the largest value of 94% among all 'summary' level commodities.

Most service commodities (light blue, light green, brown, dark purple, light purple, and light red) have less than 20-30% direct emissions, except for notable exceptions of waste management and remediation services (51%, brown), and amusements, gambling, and recreation (49%, light purple).

For commodities from government enterprises, more than 80% of their supply chain CO_2 emissions are from direct emissions: 84% (federal) and 81% (state and local).

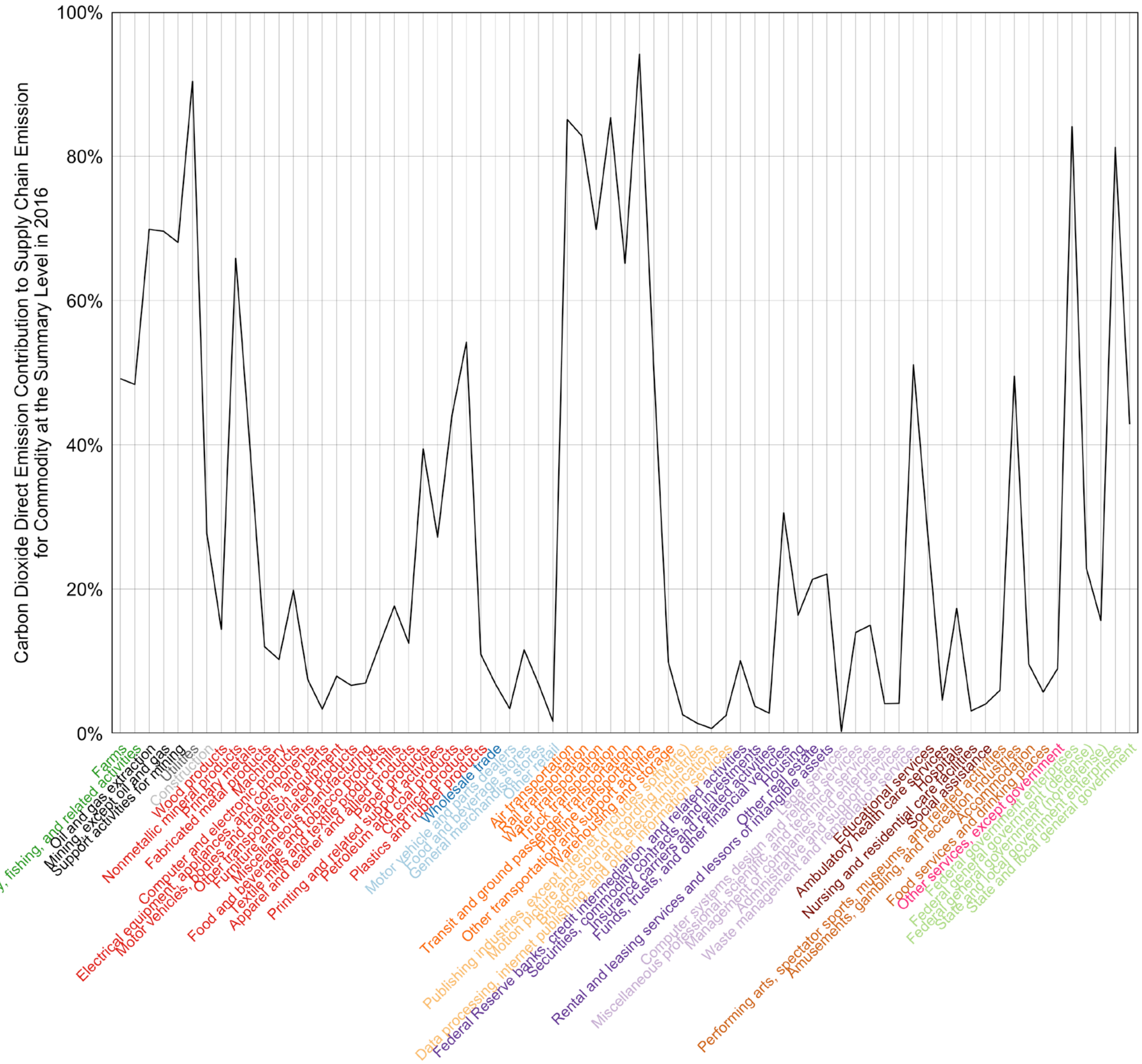


Figure 12: CO_2 direct emission contribution to supply chain emissions for commodities at the summary level in 2016.

For more than 3/4 of all US commodities, less than 20% of their supply chain CH_4 emissions are from direct emissions (Figure 13). Direct emissions make up >80% for farms (dark green) and 53% for forestry, fishing, and related activities (dark green).

Direct emissions for mining (black) commodities are >85% of total supply chain emissions. Direct emissions make up ~35% for utilities (dark grey), ~99% for pipeline transportation (dark blue), and ~90% for waste management and remediation services (brown).

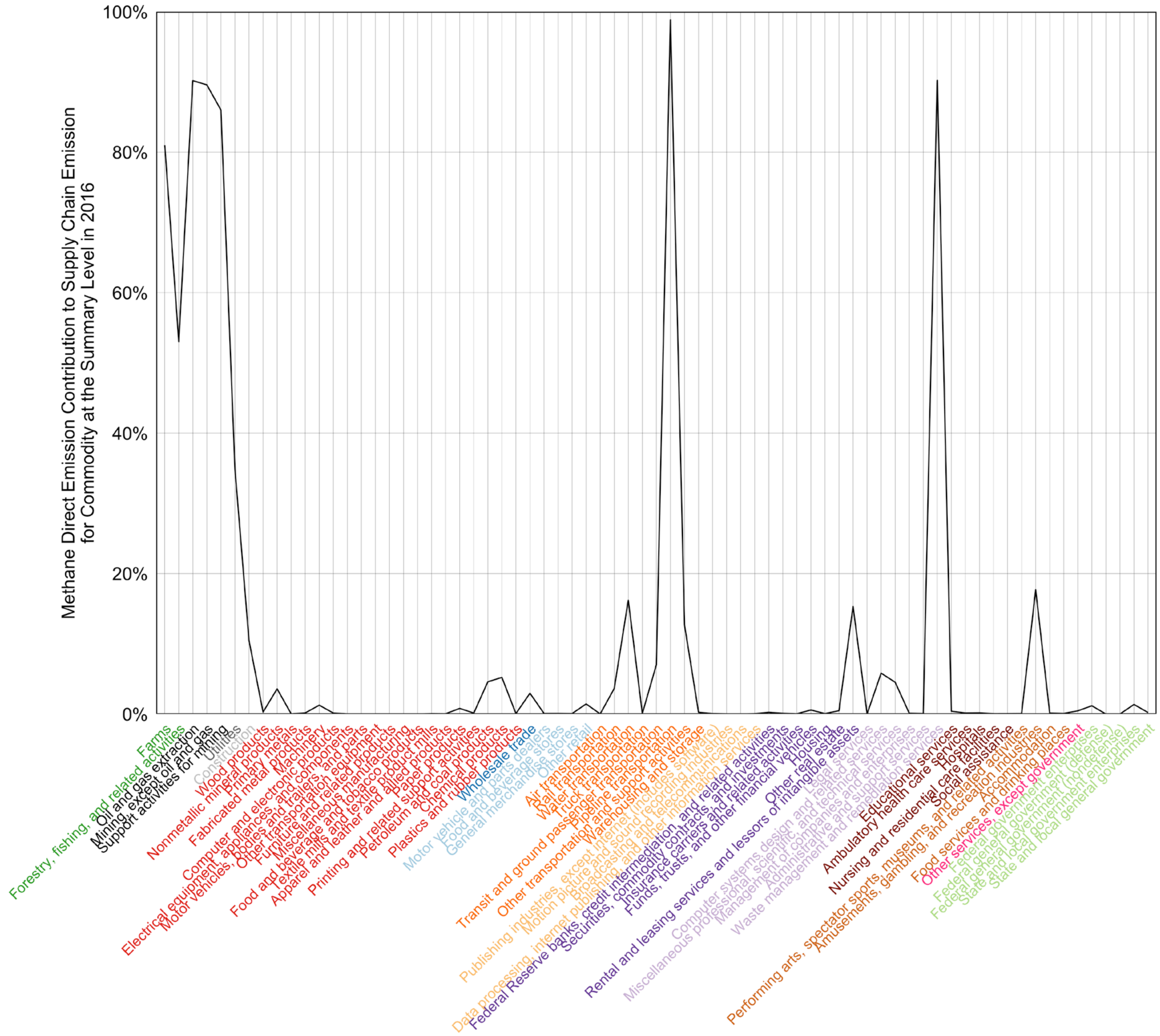


Figure 13: CH_4 direct emission contribution to supply chain emissions for commodities at the summary level in 2016.

For more than 2/3 of US commodities, less than 20% of their supply chain N_2O emissions are from direct emissions (Figure 14). Direct emissions make up >80% for farms (dark green) and ~60% for forestry, fishing, and related activities (dark green). Direct emissions from mining (black) comprise 27% of total emissions for oil and gas extraction, 54% for mining, except oil and gas, and 56% for support activities for mining. Direct emissions make up ~90% of emissions for utilities (dark grey). Direct emissions in chemical products (~50%, dark red) and computer and electronic products (~37%, dark red) are higher than other manufacturing sectors.

Direct emissions for transportation sectors (dark blue) are dominant: 73% for air transportation, 62% for rail transportation, 66% for water transportation, 45% for truck transportation, 58% for transit and ground passenger transportation, 64% for pipeline transportation, and 47% for other transportation and support activities, except for 2% for warehousing and storage.

Most service sectors (light blue, light green, brown, dark purple, light purple, and light red) have less than 20% direct emissions, except for waste management and remediation services (~75%, brown), ambulatory health care services (40%, dark purple), and amusements, gambling, and recreation industries (46%, light purple). For commodities from government enterprises, more than 80% of their supply chain N_2O emissions are from direct emissions: ~55% (federal) and ~66% (state and local).

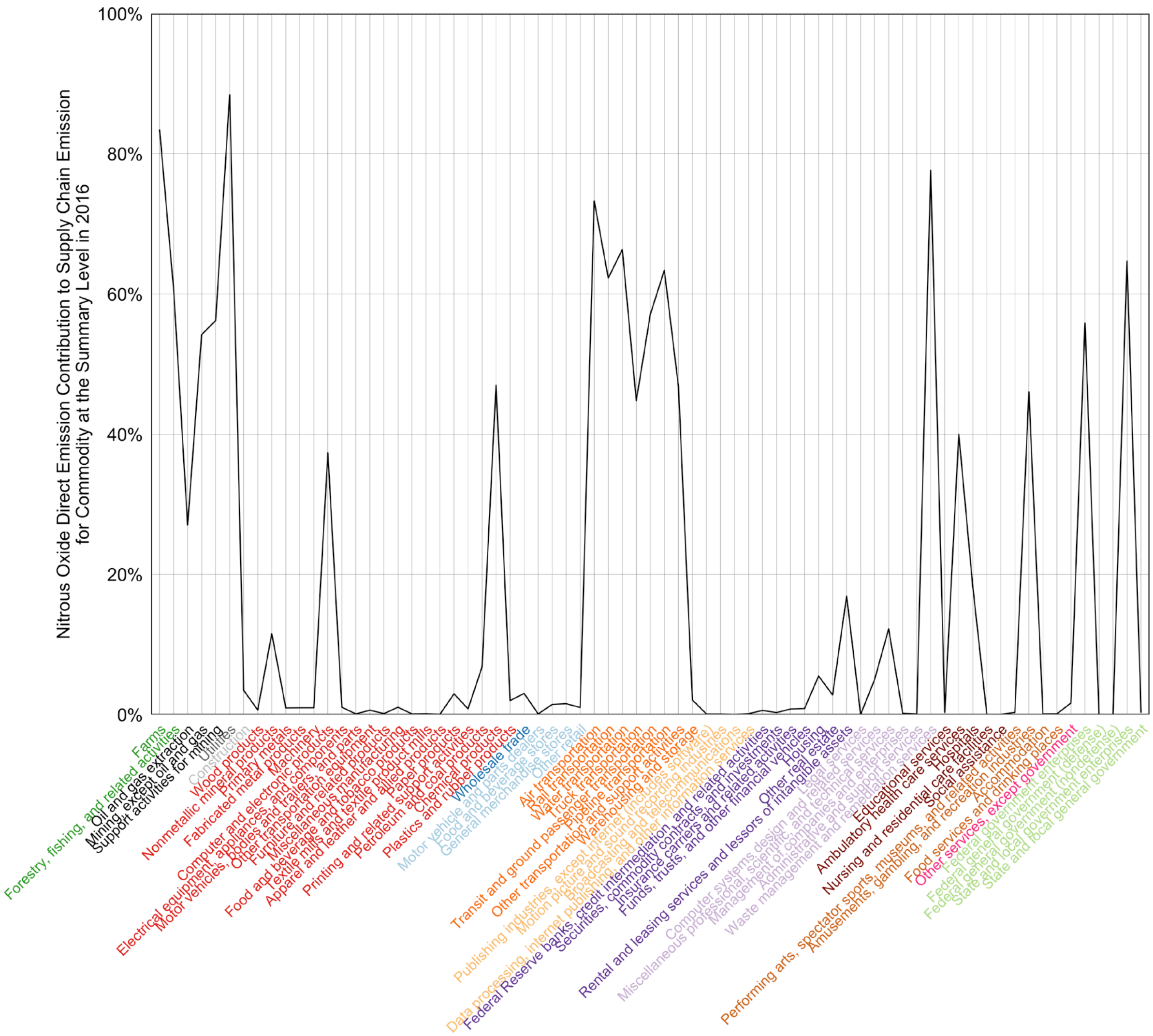


Figure 14: N2O direct emission contribution to supply chain emissions for commodities at the summary level in 2016.

3.5.2. Sector Contribution Analysis of Supply Chain Emissions

The supply chain emission factors can be better understood through analysis of those sectors in their supply chain contributing to those emissions, and assessing how those emissions change over time. Total emissions for 1 million USD output of selected manufactured goods at the summary level are shown below, broken down by goods contributing GHG emissions to these factors in their supply chains. They are presented by selected good across time, and independently for the major GHGs (Figure 15, Figure 16, and Figure 17). Similar figures are provided for all summary level commodities in Appendix 7.

Changes can be explained as one or a combination of the following factors:

1. Changes in the direct emissions associated with making the commodity OR in the direct emissions of contributing commodities.
2. Changes in the total economic requirements (see Table 1) of the commodity (see Table 11, Table 12, Table 13, Table 14, Table 15, Table 16).
3. Changes in the direct emission factors of the commodities OR in the direct emission factors of contributing commodities.

These changes can be illustrated using the Furniture SEF from 2010 to 2016 as seen in Figure 15. The direct emission factor for Furniture increases over the period, as direct emissions increase with output staying relatively constant, (see "National level gross output and direct emission trends" for 337 in Appendix 2), but this change does not appear to affect the factor significantly. The largest contribution comes from commodity 22, Utilities. We can see that the total requirement for Utilities decreases significantly (relatively) over the period from 0.035 to 0.025 (Table 13). Additionally, the direct emission factor from Utilities decreases over the period, as can be seen where emissions decrease but economic output returns to a similar level in 2016 as it was in 2010 (Figure 8). The combination of the decrease in requirements for Utilities as well as the decrease in the direct emission factor of Utilities contribute to the decrease in the Furniture supply chain emissions. Similar analysis can be performed with the other contributing sectors to fully understand how the Furniture SEF changes over the period.

For CO_2 (Figure 15), the emissions for the selected sectors decrease from 2010 to 2016, except for chemical products (325). Utilities (22), primary metals (331), chemical products (325), and truck transportation (484) and some contribution from products in the same class as the commodity of interest (e.g. ‘machinery’ for ‘machinery’) are common supply chain contributors to machinery (333), computers (334), furniture (337), food (311FT) and paper products (322). Food products (311FT) have significant contributions from farms (111CA). Decreasing utilities (22) contributions to all sectors for CO_2 can be explained by both decreasing utilities sector emissions and decreasing total requirements for utilities to make these commodities. The contribution of primary metals (331) can also be explained by decreasing direct emissions of primary metals, and decreasing requirements, although the requirements increase for some sectors in the middle of the period. Chemical products (325) direct CO_2 emissions increase over the period, resulting in an increase in total emissions of chemical products.

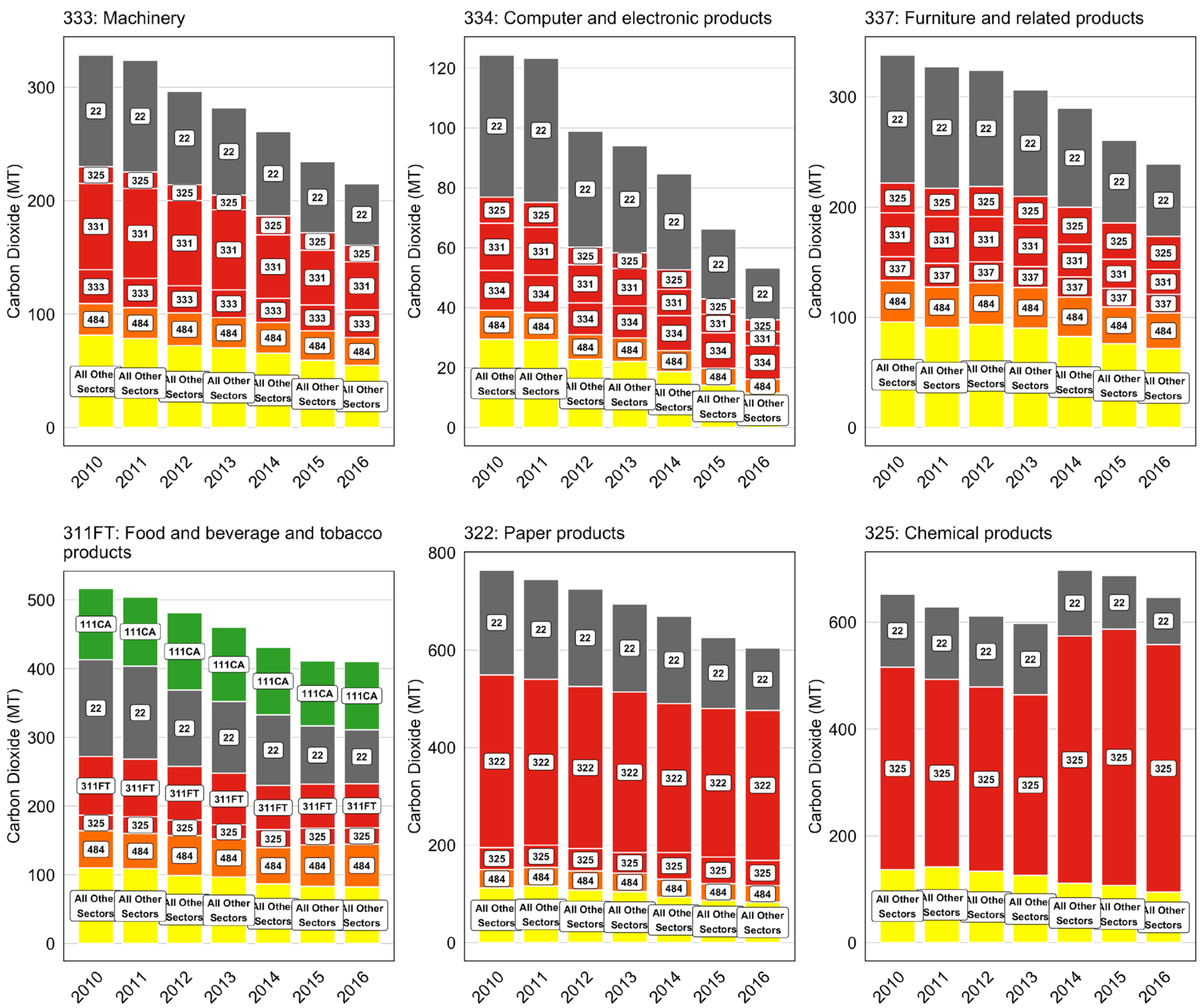


Figure 15: CO_2 industry contribution trend to supply chain emissions for selected commodities at the summary level.

For CH_4 (Figure 16), the emissions for these sectors have a decreasing trend from 2010 to 2016. Farms (111CA), mining (211 and 212), and waste management (562) are common supply chain contributors to machinery (333), computers (334), furniture (337), paper (322) and chemical products (325). Food products (311FT) have pronounced contributions from farms (111CA). Decreasing mining (211 and 212) contributions to all sectors with regard to direct CH_4 emissions can be explained by decreasing total requirements for mining activities to make these commodities as mining sector CH_4 emissions have steady increasing trend over the period.

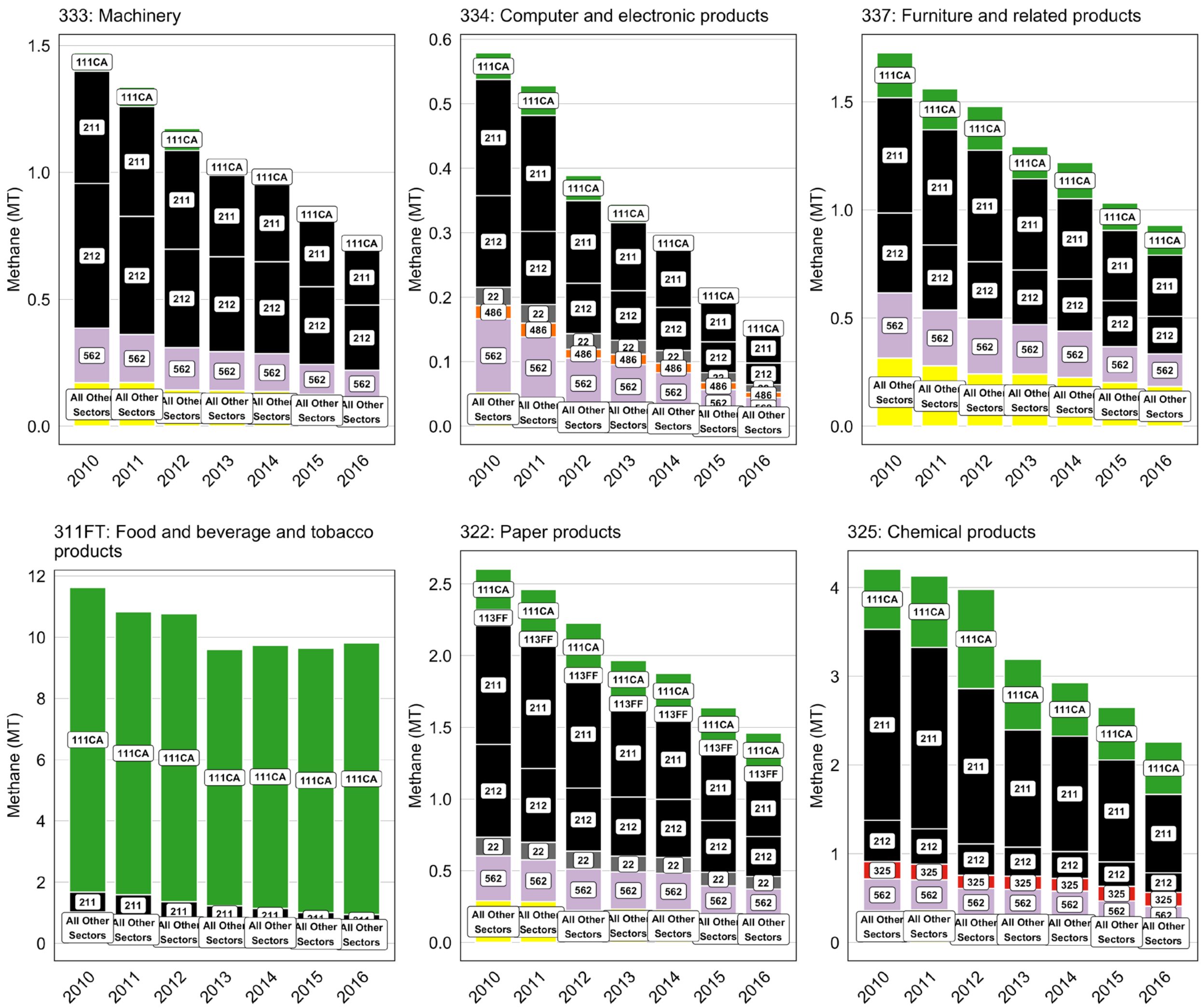


Figure 16: CH_4 industry contribution trend to supply chain emissions for selected commodities at the summary level.

For N_2O (Figure 17), the emissions for machinery (333), computer (334), paper (322), and chemical products (325) increase from 2010-2011 and subsequently decrease thereafter, whereas the emissions for furniture products (337) steadily decrease from 2010-2016 except for an uptick in 2014 (slightly exceeding 2013 level). The emissions for food products (311FT) decrease from 2010-2013 then increase until 2015 followed by a drop in 2016. Farms (111CA), utilities (22), chemical (325) and computer products (334) are common supply chain contributors to machinery (333), computers (334), furniture (337), paper (322) and chemical products (325). Similar to direct CH_4 emissions, food products (311FT) have pronounced contributions from farms (111CA).

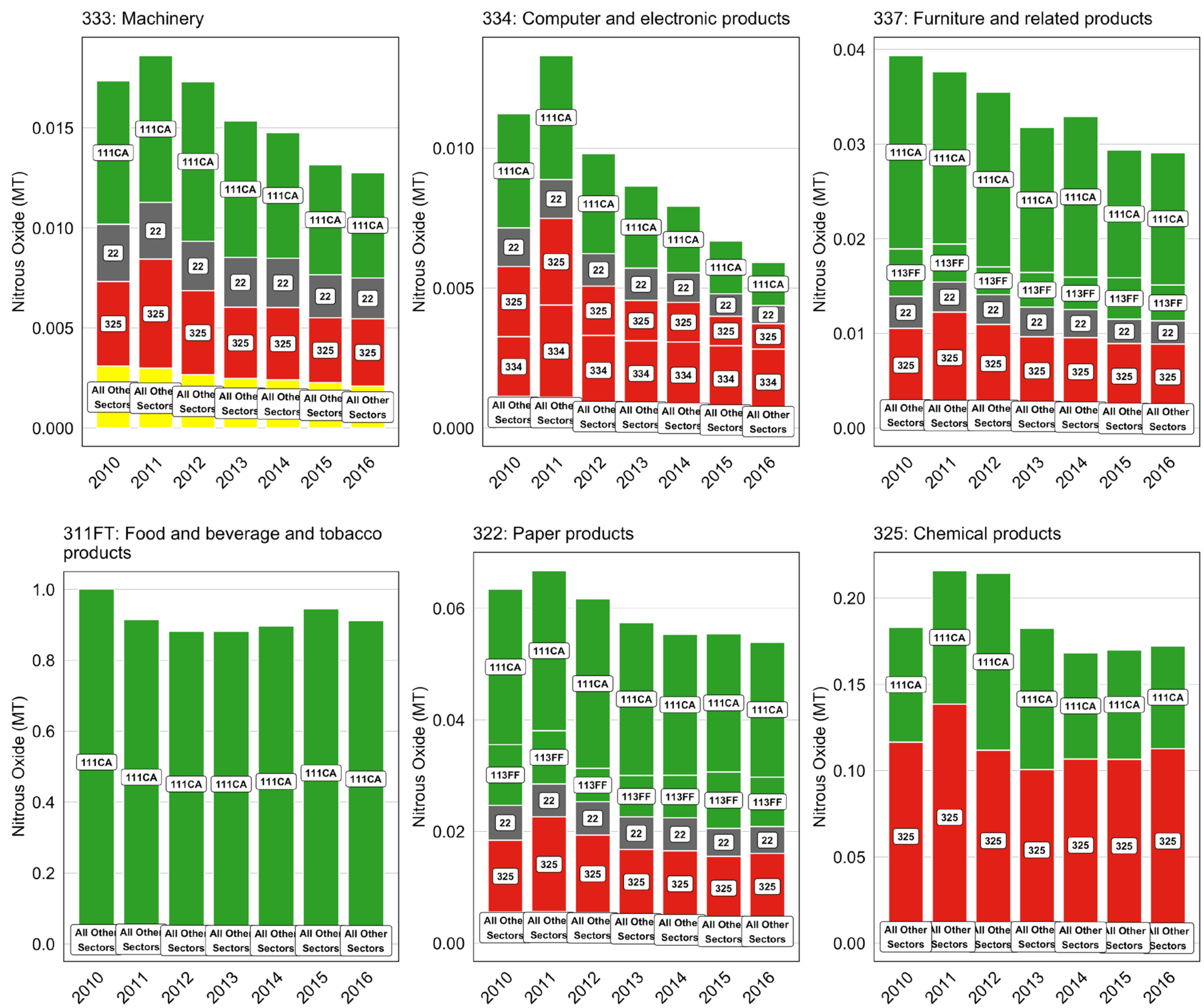


Figure 17: N_2O industry contribution trend to supply chain emissions for selected commodities at the summary level.

Table 10 contains a list of all the detailed commodities corresponding to these selected summary level commodities.

Table 10: Summary level and corresponding detail commodities for selected sectors.

Summary Level Commodities	Detail Level Commodities
Food and beverage and tobacco products	Dog and cat food, Other animal food, Flours and malts, Corn products, Soybean and other oilseed processing, Refined vegetable, olive, and seed oils, Breakfast cereals, Sugar, candy, and chocolate, Frozen food, Fruit and vegetable preservation, Cheese, Dry, condensed, and evaporated dairy, Fluid milk and butter, Ice cream and frozen desserts, Packaged poultry, Packaged meat (except poultry), Seafood, Bread and other baked goods, Cookies, crackers, pastas, and tortillas, Snack foods, Coffee and tea, Flavored drink concentrates, Seasonings and dressings, All other foods, Soft drinks, bottled water, and ice, Breweries and beer, Wineries and wine, Distilleries and spirits, Tobacco products
Paper products	Wood pulp, Paper, Cardboard, Cardboard containers, Paper bags and coated paper, Stationery, Sanitary paper (tissues, napkins, diapers, etc.), All other converted paper products
Chemical products	Petrochemicals, Compressed Gases, Synthetic dyes and pigments, Other basic inorganic chemicals, Other basic organic chemicals, Plastics, Synthetic rubber and artificial and synthetic fibers, Fertilizers, Pesticides, Medicinal and botanical ingredients, Pharmaceutical products (pills, powders, solutions, etc.), Blood sugar, pregnancy, and other diagnostic test kits, Vaccines and other biological medical products, Paints and coatings, Adhesives, Soap and cleaning compounds, Toiletries, Ink and ink cartridges, Chemicals (except basic chemicals, agrichemicals, polymers, paints, pharmaceuticals, soaps, cleaning compounds)
Machinery	Farm machinery and equipment, Lawn and garden equipment, Construction machinery, Mining and oil/gas field machinery, Semiconductor machinery, Machinery for the paper, textile, food or other industries (except semiconductor machinery), Optical instruments and lenses, Photography and photocopying equipment, Other commercial and service industry machinery, Industrial and commercial fan and blower and air purification equipment, Heating equipment other than warm air furnaces, Air conditioning, refrigeration, and warm air heating equipment, Industrial molds, Special tools, dies, jigs, and fixtures, Machine tool manufacturing, Cutting and machine tool accessory, rolling mill, and other metalworking machines, Turbines and turbine generator sets, Speed changers, industrial high-speed drives, and gears, Mechanical power transmission equipment, Other engine equipment, Air and gas compressors, Pumps and pumping equipment, Material handling equipment, Power tools, Packaging machinery, Industrial process furnaces and ovens, Welding and Soldering Equipment, Scales and Balances, and other general purpose machinery, Hydraulic pumps, motors, cylinders and actuators
Computer and electronic products	Computers, Computer storage device readers, Computer terminals and other computer peripheral equipment, Telephones, Wireless communications, Communications equipment, Audio and video equipment, Semiconductors, Printed circuit and electronic assembly, Electronic capacitors, resistors, coils, transformers, connectors and other components (except semiconductors and printed circuit assemblies), Electromedical appartuses, Navigation instruments, Automatic controls for HVAC and refrigeration equipment, Industrial process variable instruments, Fluid meters and counting devices, Signal testing instruments, Analytical laboratory instruments, Irradiation apparatuses, Watches, clocks, and other measuring and controlling devices, External hard drives, CDs, other storage media
Furniture and related products	Wood kitchen cabinets and countertops, Home furniture - upholstered, Home furniture - wood, nonupholstered, Institutional furniture, Other household nonupholstered furniture, Shelving and lockers, Office furniture and custom architectural woodwork and millwork, Mattresses, blinds and shades

The total requirements tables for these selected manufactured commodities are presented below for aid in understanding the supply chain contribution trends. Total requirements (in producer value) are shown only for commodities contributing significantly to the supply chain emissions for one or more selected manufactured commodity, and for one or more of the major gases.

These total requirements have not been adjusted to 2018 USD but are in the dollar year matching the column year, which is how the total requirements are used in the USEEIO models.

Table 11: Total requirements from contributing sectors to machinery (333). Values are unitless, calculated as dollar of commodities from contributing sectors divided by one dollar of output from the machinery sector.

Source Sector	Sector Name	2010	2011	2012	2013	2014	2015	2016
111CA	Farms	0.002	0.003	0.004	0.003	0.003	0.002	0.002
211	Oil and gas extraction	0.022	0.025	0.022	0.021	0.022	0.011	0.008
212	Mining, except oil and gas	0.018	0.020	0.017	0.015	0.015	0.012	0.010
22	Utilities	0.030	0.031	0.027	0.027	0.028	0.024	0.021
325	Chemical products	0.054	0.060	0.058	0.055	0.051	0.043	0.042
331	Primary metals	0.189	0.224	0.215	0.202	0.194	0.165	0.148
333	Machinery	1.100	1.106	1.111	1.101	1.103	1.111	1.107
484	Truck transportation	0.021	0.022	0.025	0.024	0.025	0.024	0.022
562	Waste management and remediation services	0.004	0.004	0.003	0.003	0.003	0.003	0.003

Table 12: Total requirements from contributing sectors to computers and electronic products (334). Values are unitless, calculated as dollar of commodities from contributing sectors divided by one dollar of output from the computers and electronic products sector.

Source Sector	Sector Name	2010	2011	2012	2013	2014	2015	2016
111CA	Farms	0.001	0.002	0.002	0.001	0.001	0.001	0.001
211	Oil and gas extraction	0.009	0.011	0.007	0.007	0.006	0.003	0.002
212	Mining, except oil and gas	0.005	0.005	0.003	0.003	0.003	0.002	0.001
22	Utilities	0.014	0.015	0.013	0.012	0.012	0.009	0.007
325	Chemical products	0.032	0.034	0.024	0.022	0.020	0.014	0.011
331	Primary metals	0.039	0.045	0.036	0.036	0.030	0.021	0.016
334	Computer and electronic products	1.142	1.133	1.108	1.102	1.092	1.081	1.065
484	Truck transportation	0.007	0.007	0.007	0.007	0.007	0.005	0.004
486	Pipeline transportation	0.001	0.001	0.000	0.001	0.001	0.000	0.000
562	Waste management and remediation services	0.002	0.002	0.002	0.001	0.001	0.001	0.001

Table 13: Total requirements from contributing sectors to furniture and related products (337). Values are unitless, calculated as dollar of commodities from contributing sectors divided by one dollar of output from the furniture sector.

Source Sector	Sector Name	2010	2011	2012	2013	2014	2015	2016
111CA	Farms	0.007	0.007	0.008	0.007	0.008	0.005	0.005
113FF	Forestry, fishing, and related activities	0.020	0.020	0.018	0.018	0.019	0.019	0.019
211	Oil and gas extraction	0.026	0.031	0.030	0.027	0.027	0.013	0.010
212	Mining, except oil and gas	0.012	0.013	0.012	0.010	0.010	0.008	0.007
22	Utilities	0.035	0.035	0.035	0.033	0.033	0.029	0.025
325	Chemical products	0.100	0.106	0.115	0.112	0.102	0.092	0.086
331	Primary metals	0.099	0.120	0.117	0.108	0.103	0.091	0.079
337	Furniture and related products	1.065	1.072	1.053	1.053	1.056	1.057	1.056
484	Truck transportation	0.028	0.030	0.033	0.033	0.033	0.030	0.029
562	Waste management and remediation services	0.006	0.005	0.005	0.005	0.005	0.004	0.004

Table 14: Total requirements from contributing sectors to food and beverage and tobacco (311FT). Values are unitless, calculated as dollar of commodities from contributing sectors divided by one dollar of output from the food sector.

Source Sector	Sector Name	2010	2011	2012	2013	2014	2015	2016
111CA	Farms	0.322	0.360	0.392	0.383	0.399	0.354	0.331
211	Oil and gas extraction	0.032	0.040	0.035	0.033	0.032	0.016	0.013
22	Utilities	0.043	0.043	0.037	0.036	0.038	0.033	0.030
311FT	Food and beverage and tobacco products	1.264	1.293	1.295	1.280	1.273	1.269	1.264
325	Chemical products	0.083	0.100	0.095	0.088	0.079	0.068	0.067
484	Truck transportation	0.040	0.042	0.051	0.049	0.049	0.055	0.056

Table 15: Total requirements from contributing sectors to paper products (322). Values are unitless, calculated as dollar of commodities from contributing sectors divided by one dollar of output from the paper products sector.

Source Sector	Sector Name	2010	2011	2012	2013	2014	2015	2016
111CA	Farms	0.009	0.012	0.014	0.012	0.011	0.009	0.009
113FF	Forestry, fishing, and related activities	0.043	0.048	0.036	0.036	0.043	0.044	0.045
211	Oil and gas extraction	0.040	0.050	0.043	0.040	0.040	0.019	0.014
212	Mining, except oil and gas	0.021	0.022	0.019	0.017	0.017	0.014	0.011
22	Utilities	0.066	0.065	0.066	0.062	0.067	0.056	0.049
322	Paper products	1.310	1.312	1.304	1.312	1.307	1.297	1.291
325	Chemical products	0.166	0.188	0.193	0.181	0.166	0.153	0.147
484	Truck transportation	0.028	0.031	0.034	0.034	0.034	0.031	0.031
562	Waste management and remediation services	0.006	0.006	0.006	0.006	0.006	0.005	0.005

Table 16: Total requirements from contributing sectors to chemical products (325). Values are unitless, calculated as dollar of commodities from contributing sectors divided by one dollar of output from the chemical products sector.

Source Sector	Sector Name	2010	2011	2012	2013	2014	2015	2016
111CA	Farms	0.022	0.031	0.047	0.036	0.028	0.024	0.022
211	Oil and gas extraction	0.105	0.119	0.100	0.086	0.093	0.047	0.031
212	Mining, except oil and gas	0.015	0.017	0.016	0.013	0.013	0.011	0.008
22	Utilities	0.042	0.043	0.044	0.046	0.046	0.039	0.034
325	Chemical products	1.403	1.446	1.453	1.453	1.402	1.345	1.321
562	Waste management and remediation services	0.007	0.007	0.007	0.007	0.007	0.005	0.005

3.5.3. Comparing Commodity-Based and Industry-Based Supply Chain Factors

Since we calculate both commodity-based and industry-based supply chain emissions factor and users will likely choose based on whether they are estimating GHG emissions associated with purchases from a given industry or for a commodity, we compare these factors to evaluate how these factors differ based on that selection. The same sectoral classification is used for commodities and industries, which enables straightforward comparisons.

Differences in commodity vs. industry SEFs are generally found when a commodity is produced by more than one industry (a primary industry and other industries producing secondary products), and these industries have different supply chain emissions.

For 'summary' level supply chain emission factors, we further inspect the difference between commodity- and industry-based supply chain emission factors in Figure 18, Figure 19, Figure 20. Similar figures showing this difference in detail level commodity and industry factors are provided in Appendix 9.

Industry SEFs for CO_2 for utilities are significantly higher than commodity SEFs. The electricity commodity is made by the Utilities industry (76%), but the State and local government enterprises (24) make ~21.5%, and other industries make smaller proportions of utilities. These two industries have widely differing SEFs, of 3.4 and 1.2 kg/$, which get averaged using the output proportion of Utilities as a weighting factor. This effectively lowers the Utilities commodity SEF in relation to the Utilities industry SEF. The combination of industries producing a commodity can have the opposite effect as well, increasing the commodity SEF in relation to the primary industry SEF, as is seen in Transit and ground passenger transportation commodity in Figure 18.

Most sectors have differences for CO_2 factors between -0.02 and 0.02 kg/$ over the period of 2012-2016 (Figure 18). The largest difference is found in utilities (dark grey), which decreases from 0.68 kg/$ in 2012 to 0.43 kg/$ in 2014 then increases to 0.65 kg/$ in 2016. Transit and ground passenger transportation (dark blue) has smaller industry CO_2 factors than commodity CO_2 factors, and the difference increases from -0.31 kg/$ in 2010 to -0.19 kg/$ in 2016. A similar trend is also found in the amusements, gambling, and recreation industries (light purple): increasing from -0.22 kg/$ in 2010 to -0.17 kg/$ in 2016. The difference for support activities for mining (black) decreases from -0.07 kg/$ in 2012 to -0.14 kg/$ in 2016 except for a increase in 2014, while the difference for pipeline transportation (dark blue) first decreases from -0.156 kg/$ in 2012 to -0.16 kg/$ in 2014 then increases to -0.12 kg/$ in 2016.

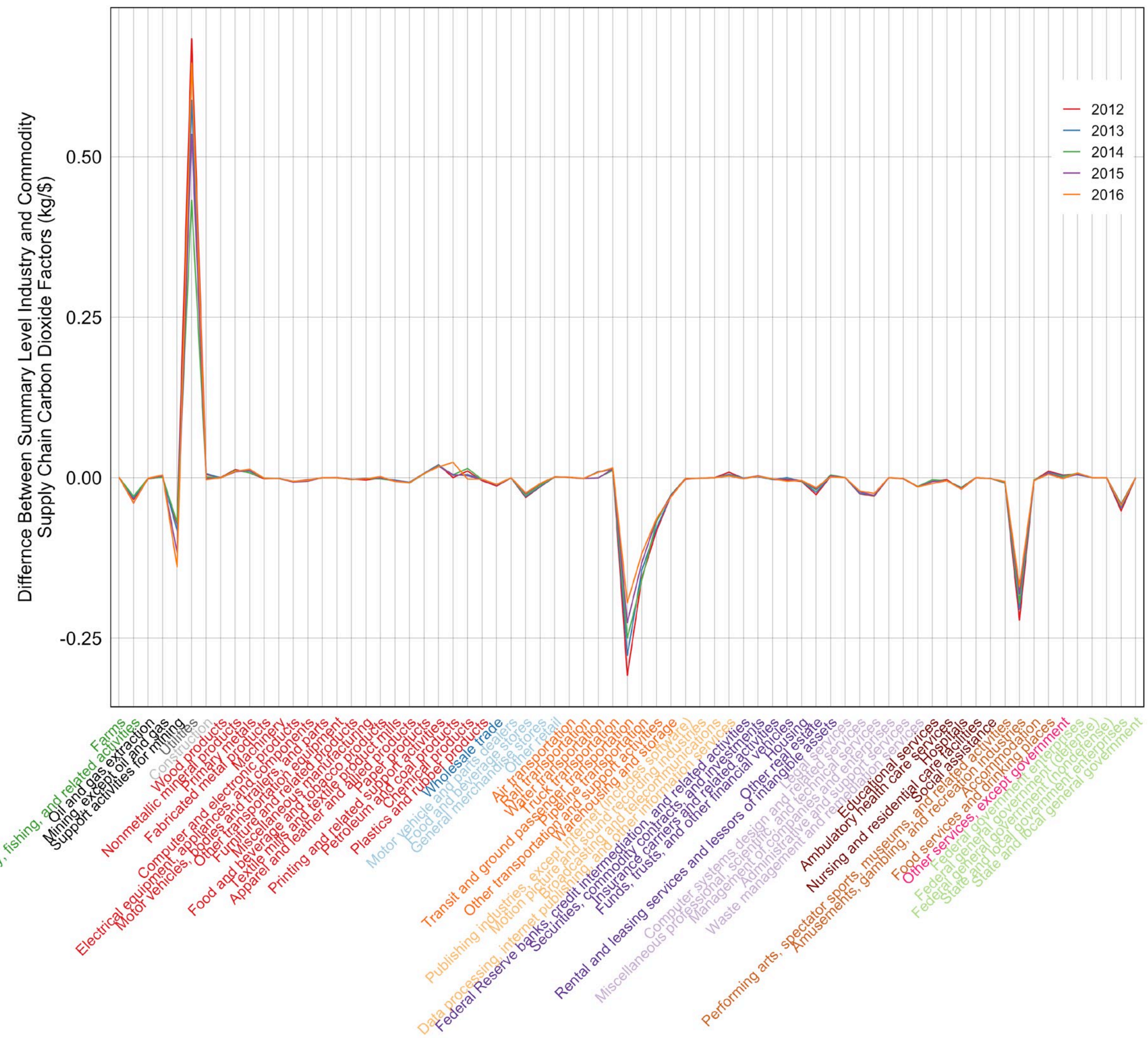


Figure 18: Difference between summary level industry and commodity CO_2 supply chain emission factors

Most sectors have the differences for CH_4 factors between -1 and 1 g/$ over the period of 2012-2016 (Figure 19). Support activities for mining (black) has smaller industry CH_4 factors than commodity CH_4 factors, and the difference decreases from -6.8 g/$ in 2012 to -7.1 g/$ in 2013 then increased in 2014 but decreased to -13.4 g/$ in 2016. Forestry, fishing, and related activities (dark green) also has industry CH_4 factors smaller than commodity CH_4 factors. The difference decreased from -2.37 g/$ in 2012 to -2.40 g/$ in 2013 then increased to -2.37 g/$ in 2016. The difference for CH_4 factors are larger than 1g/$ for waste management and remediation services (brown) and pipeline transportation (dark blue). Difference of the former decreased from 10.3 g/$ in 2012 to 7.5 g/$ in 2016, while difference of the latter increased from 2.80 g/$ in 2012 to 2.85 g/$ in 2013 then decreases to 1.7 g/$ in 2016.

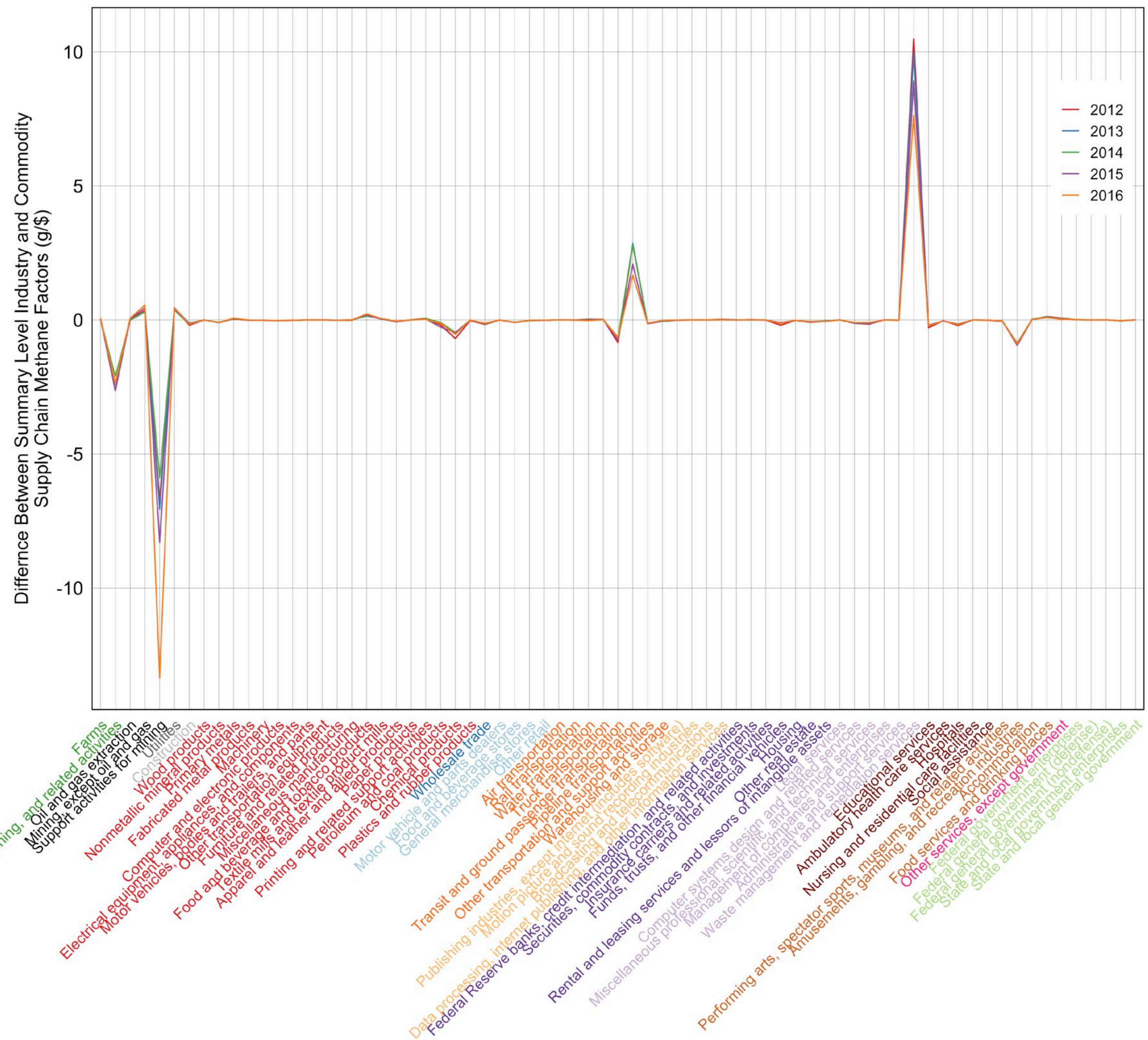


Figure 19: Difference between summary level industry and commodity CH_4 supply chain emission factors

Most sectors have the differences for N_2O factors between -0.05 and 0.01 g/$ over the period of 2012-2016 (Figure 20). Forestry, fishing, and related activities (dark green) has smaller industry N_2O factors than commodity N_2O factors, and the difference decreases from -0.21 g/$ in 2012 to -0.27 g/$ in 2015 then increases to -0.23 g/$ in 2016. Amusements, gambling, and recreation industries (light purple) also has smaller industry N_2O factors than commodity N_2O factors. The difference decreases from -0.028 g/$ in 2012 to -0.044 g/$ in 2013 then increases to -0.38 g/$ in 2016. The difference for N_2O factors are larger than 0.01g/$ for food and beverage and tobacco products (dark red) and utilities (dark grey). Difference of the former decreasing from 0.018 g/$ in 2012 to 0.021 g/$ in 2016, while difference of the latter increases from 0.024 g/$ in 2012 to 0.028 g/$ in 2016.

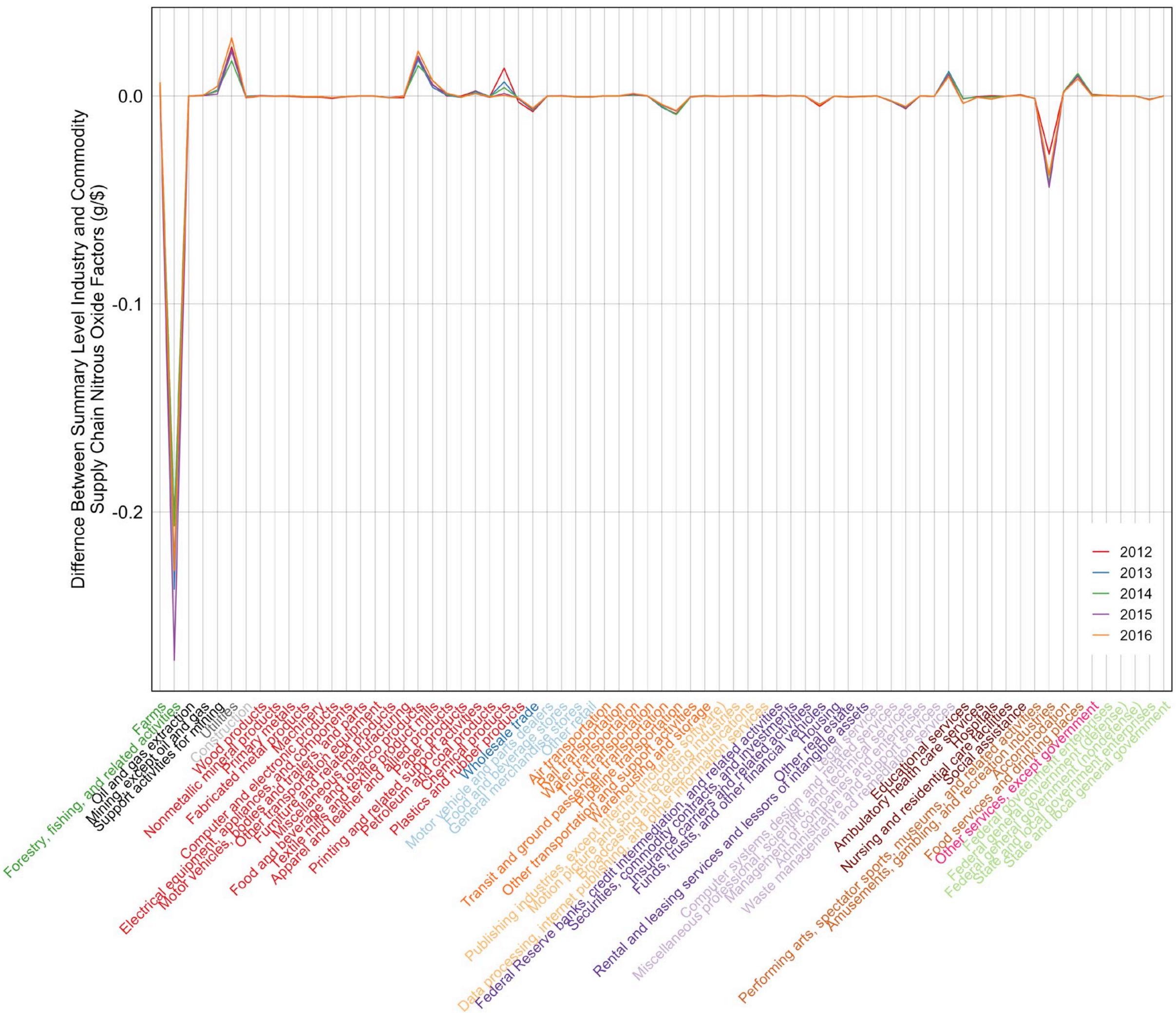


Figure 20: Difference between summary level industry and commodity N_2O supply chain emission factors

3.5.4. Comparing Summary-level and Detail-level Supply Chain Factors

Our presentation of the supply chain factors has focused on those prepared at the 'summary' level of sectoral aggregation, but they were also generated at the 'detail' level for 350+ industries and commodities. Because these factors were produced from different USEEIO models with different underlying IO tables, the factor values for 'detail' level commodities may differ from those at the 'summary' level. We select the same six 'summary' level manufacturing sectors used in the contribution analysis, and compare their supply chain emission factors against their corresponding 'detail' level commodity factors (Figure 21, Figure 22, Figure 23), each produced by USEEIO models using 2016 GHG emissions data and converted to 2018 USD in producer value. Differences between summary and detail level DEFs and SEFs for all commodities are presented in Appendix 8.

For CO_2 (Figure 21), 'summary' level supply chain emission factors are all smaller than the median of 'detail' level factors. The factor for furniture products is even smaller than all 'detail' level factors. For food products, 'detail' level factors range from 0.17 to 0.77 kg/$ with a median of 0.49 kg/$, while the 'summary' level factor is 0.42 kg/$. For paper products, 'detail' level factors range from 0.59 to 1.15 kg/$ with a median of 0.73 kg/$, while the 'summary' level factor is 0.66 kg/$. 'Detail' level factors for chemical products have the largest range from 0.09 to 1.92 kg/$ with a median of 0.77 kg/$, while the 'summary' level factor is 0.71 kg/$. For machinery, 'detail' level factors range from 0.16 to 0.45 kg/$ with a median of 0.27 kg/$, while the 'summary' level factor is 0.23 kg/$. 'Detail' level factors for computer and electronics have the smallest range from 0.05 to 0.18 kg/$ with a median of 0.10 kg/$, while the 'summary' level factor is 0.05 kg/$. For furniture products, 'detail' level factors range from 0.31 to 0.48 kg/$ with a median of 0.36 kg/$, while the 'summary' level factor is 0.25 kg/$.

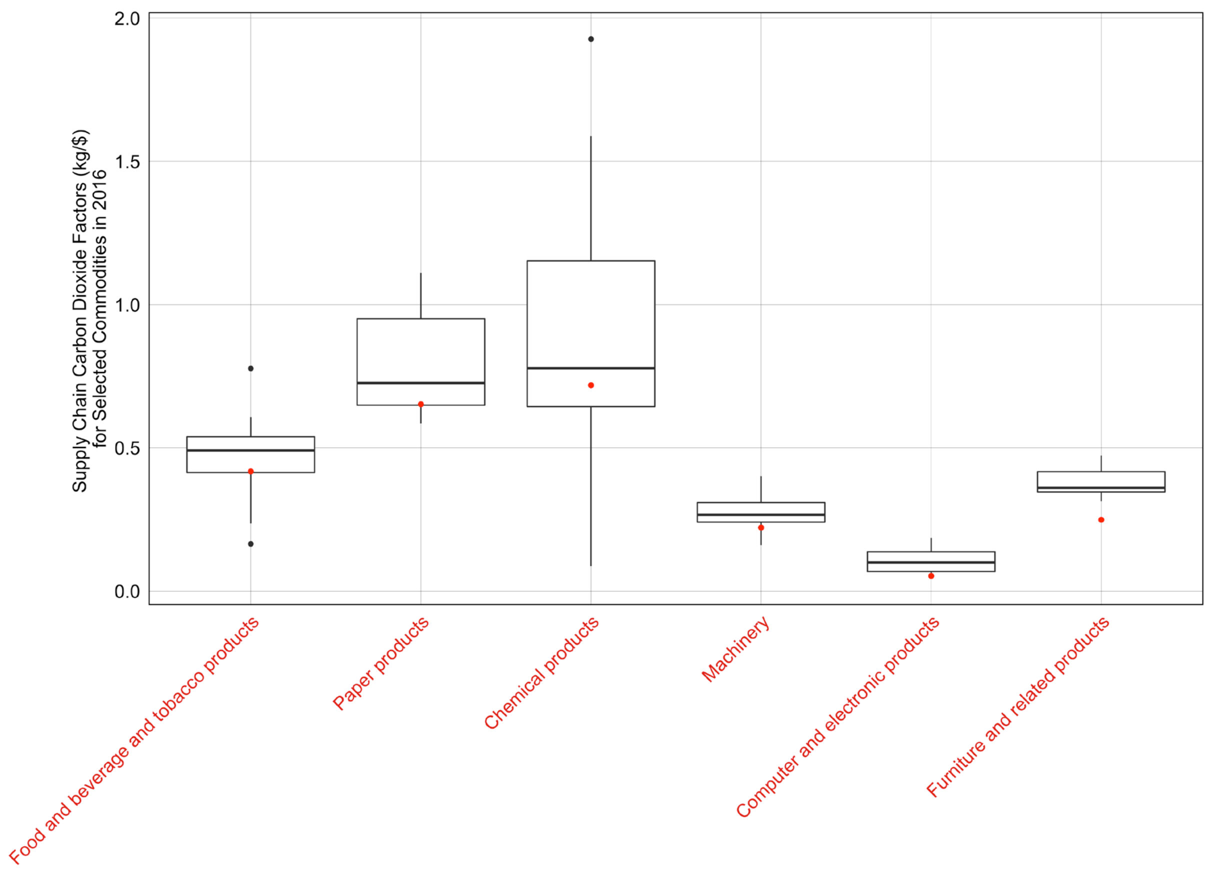


Figure 21: Comparison of summary level (red point) and detailed level (box plot) CO_2 SEFs for selected commodities in 2016. Each boxplot shows the distribution of 'detail' level supply chain emission factors: horizontal thick black line is the median, boxes represents the 25-75 percentile range, and whisker lengths are 1.5 times the interquartile range. Black points represent 'detail' level outliers, while red points represent 'summary' level supply chain emission factors.

For CH_4 (Figure 22), 'summary' level supply chain emission factors are all smaller, than the median of 'detail' level factors, except for food products. 'detail' level factors for food products have the largest range from 0.68 to 54.42 g/$ with a median of 3.85 g/$, while the 'summary' level factor is 10.00 g/$. For paper products, 'detail' level factors range from 2.03 to 3.78 g/$ with a median of 2.35 g/$, while the 'summary' level factor is 1.59 g/$. For chemical products, 'detail' level factors range from 0.32 to 8.25 g/$ with a median of 2.76 g/$, while the 'summary' level factor is 2.67 g/$. For machinery, 'detail' level factors range from 0.60 to 1.46 g/$ with a median of 1.04 g/$, while the 'summary' level factor is 0.81 g/$. 'Detail' level factors for computer and electronics have the smallest range from 0.15 to 0.61 g/$ with a median of 0.34 g/$, while the 'summary' level factor is 0.16 g/$. For furniture products, 'detail' level factors range from 1.23 to 1.90 g/$ with a median of 1.42 g/$, while the 'summary' level factor is 0.97 g/$.

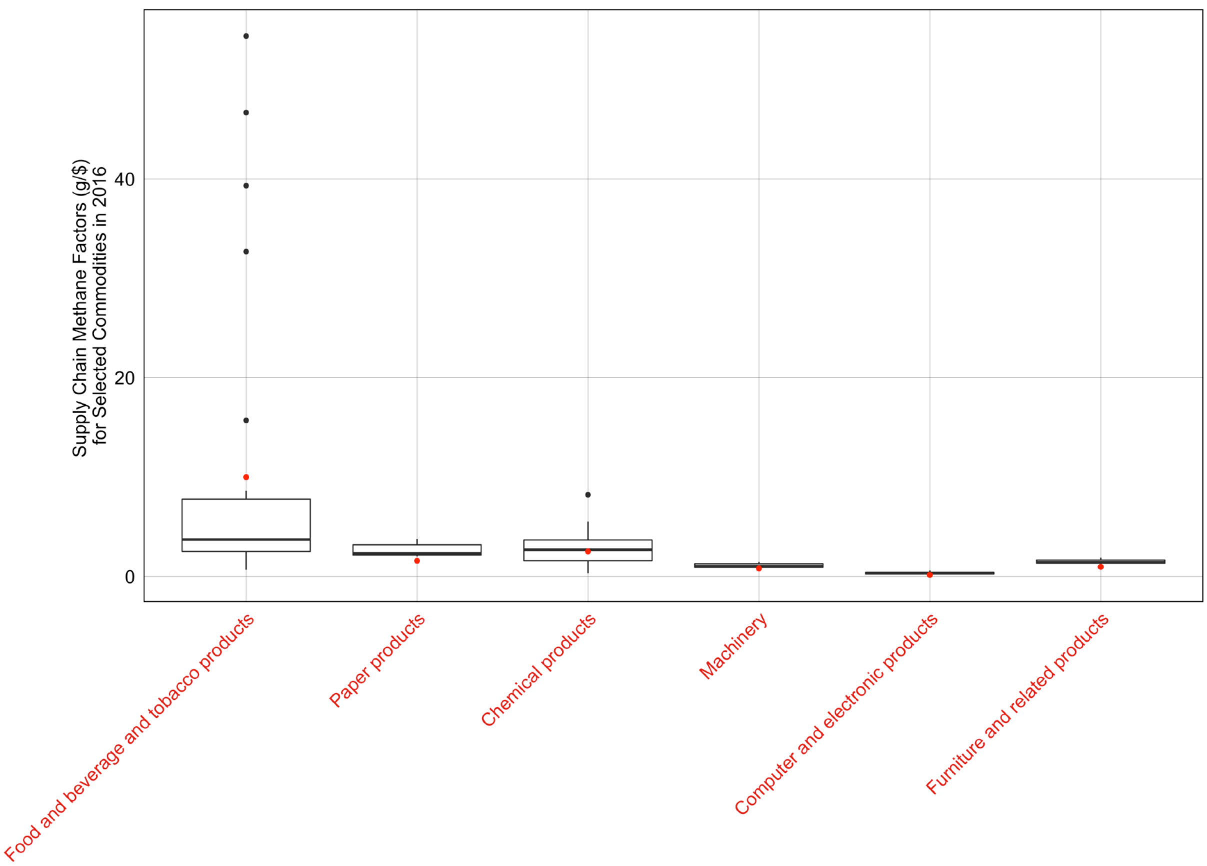


Figure 22: Comparison of summary level (red point) and detailed level (box plot) CH_4 SEFs for selected commodities in 2016. Each boxplot shows the distribution of 'detail' level supply chain emission factors: horizontal thick black line is the median, boxes represents the 25-75 percentile range, and whisker lengths are 1.5 times the interquartile range. Black points represent 'detail' level outliers, while red points represent 'summary' level supply chain emission factors.

For N_2O (Figure 23), 'summary' level supply chain emission factors are all smaller than the median of 'detail' level factors, except for food and chemical products. 'Detail' level factors for food products have the largest range from 0.11 to 2.81 g/$ with a median of 0.66 g/$, while the 'summary' level factor is 0.93 g/$. For paper products, 'detail' level factors range from 0.06 to 0.13 g/$ with a median of 0.10 g/$, while the 'summary' level factor is 0.06 g/$. For chemical products, 'detail' level factors range from 0.01 to 2.21 g/$ with a median of 0.16 g/$, while the 'summary' level factor is 0.20 g/$. For machinery, 'detail' level factors range from 0.01 to 0.05 g/$ with a median of 0.02 g/$, while the 'summary' level factor is 0.01 g/$. 'Detail' level factors for computer and electronics have the smallest range from 0.004 to 0.02 g/$ with a median of 0.009 g/$, while the 'summary' level factor is 0.006 g/$. For furniture products, 'detail' level factors range from 0.03 to 0.06 g/$ with a median of 0.04 g/$, while the 'summary' level factor is 0.03 g/$.

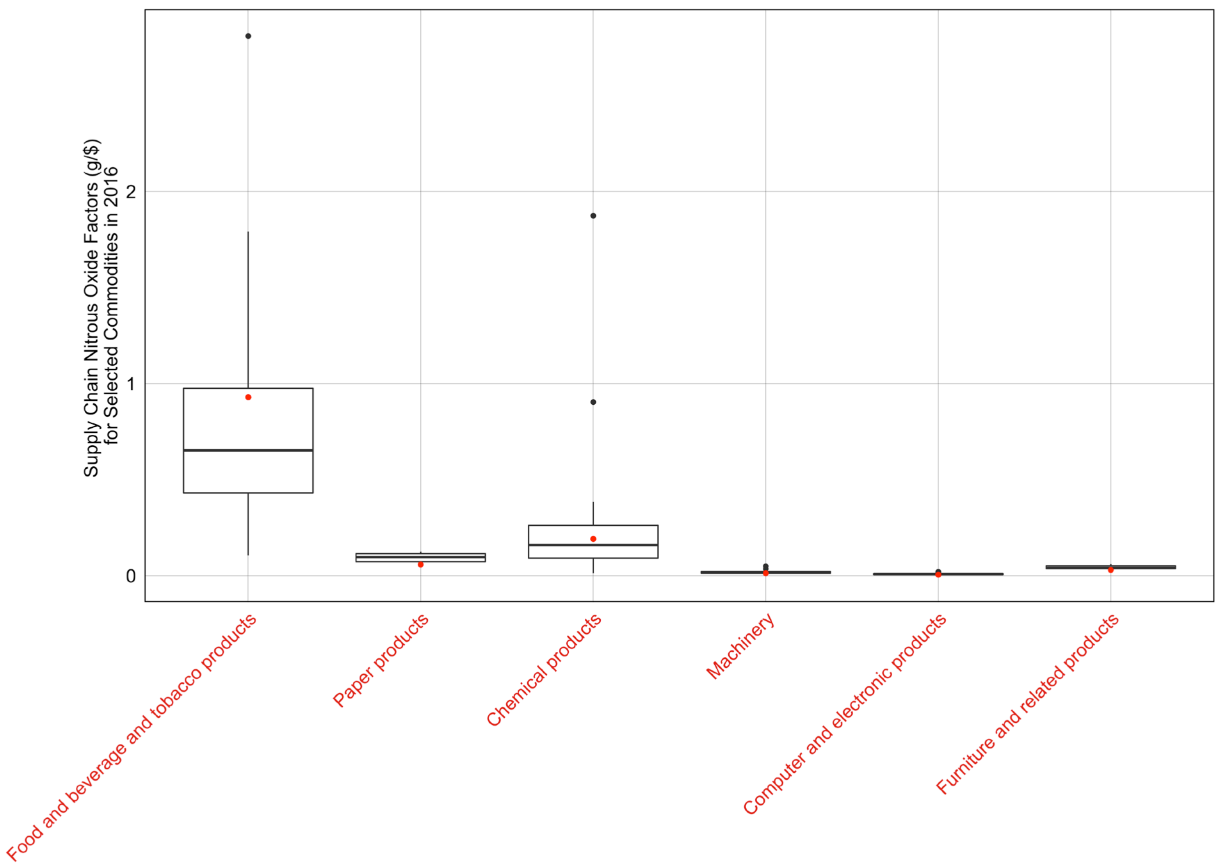


Figure 23: Comparison of summary level (red point) and detailed level (box plot) N_2O SEFs for selected commodities in 2016. Each boxplot shows the distribution of 'detail' level supply chain emission factors: horizontal thick black line is the median, boxes represents the 25-75 percentile range, and whisker lengths are 1.5 times the interquartile range. Black points represent 'detail' level outliers, while red points represent 'summary' level supply chain emission factors.

The detailed level commodities corresponding to these summary level commodities are listed in Table 10.

3.5.5. Validation Results

Summary level SEFs built with total domestic requirements and scaled by total national final demand (SEF scaled result) equaled the national GHG totals extracted from the National GHG Industry Attribution model, demonstrating perfect additive correspondence. The detailed SEFs demonstrated the same for 2012, except for minor differences (<-6%) for CO_2 and N_2O for commodities in this year. For years prior to and after 2012, the SEF scaled result departed from the national totals by -12% to 7%. This departure is explained by the pairing of current year GHG emission data with total requirements calculated with static 2012 IO tables. A summary figure of validation results for all models is presented in Appendix 10.

3.5.6. Data Quality Assessment

The SEF data quality assessment results reveal excellent temporal and geographical representativeness and data collection scores for the 2016 'summary' level commodity model factors. The data reliability and technological representativeness scores are more variable across the commodity factors. Most factors are derived by data based on documented estimates, resulting in a common score of 4 for data reliability, or 3 in some cases where some of the underlying data are based on verified calculations (a score of 2) and these scored are averaged. The technological correlation is generally a score of 3-4, indicating imperfect correlation between the designated commodity and the technologies from which underlying GHG emissions data derive. This is explained by the allocation of original GHG emissions data in most cases across technologies based on supporting, non-GHG data, such as energy use or amount of purchases of a given commodity that results in the GHG emissions of interest. The data reliability and technological correlation scores do vary across the major gases by commodity, in which cases where specific gases from specific industries are directly reported in the GHG Inventory.

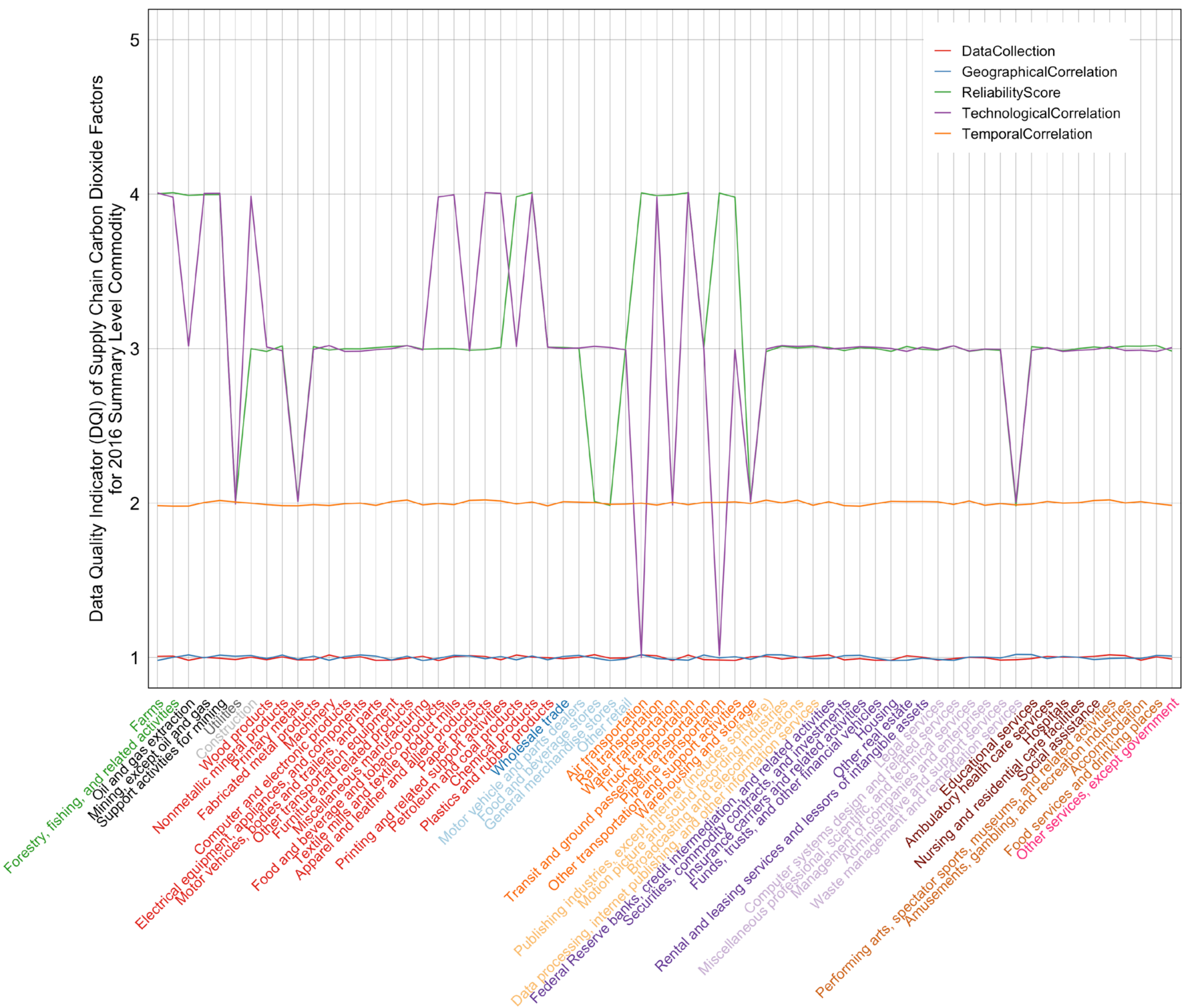


Figure 24: Data quality scores of supply chain CO2 factors for 2016 summary level commodities

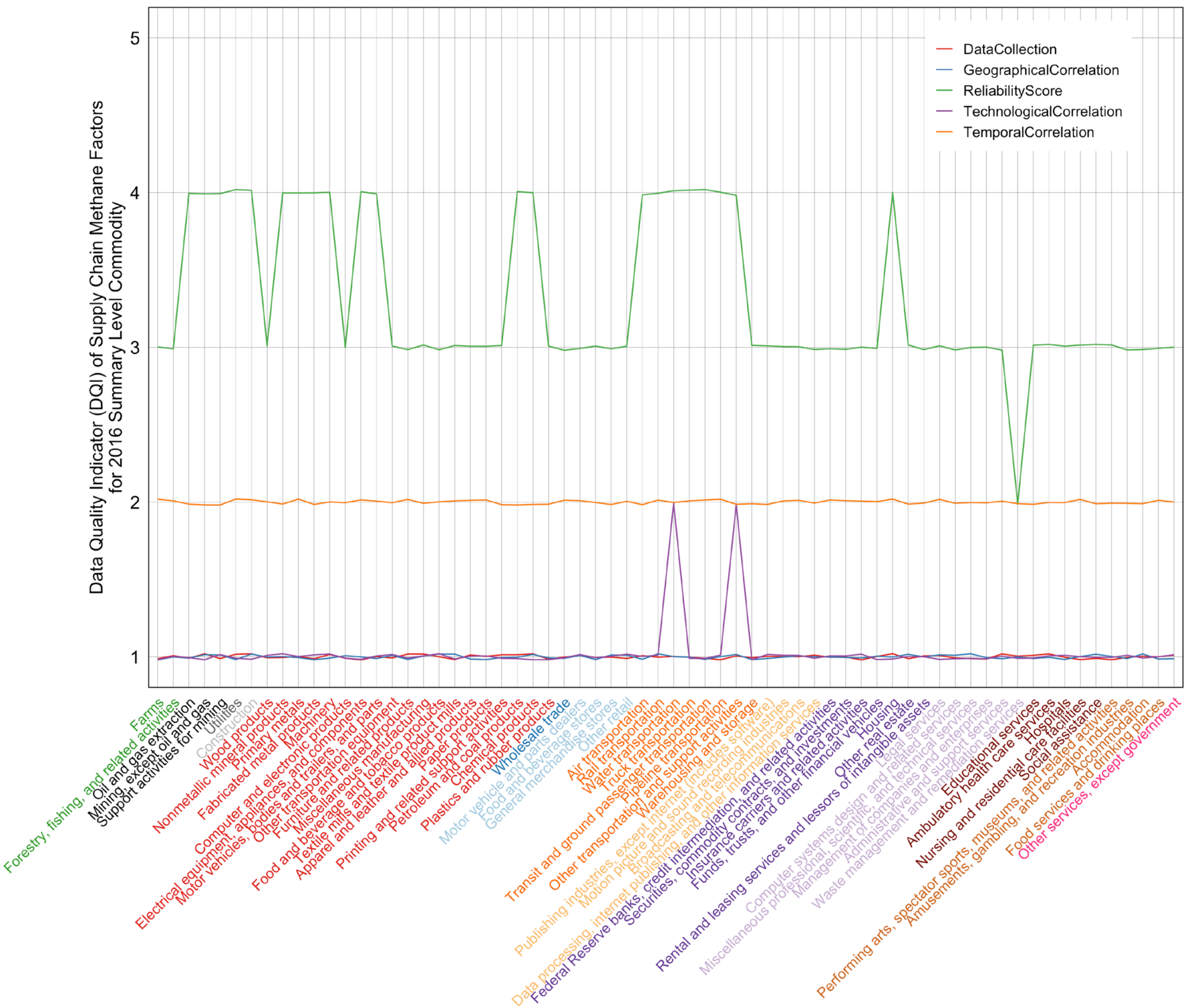


Figure 25: Data quality scores of supply chain CH_4 factors for 2016 summary level commodities

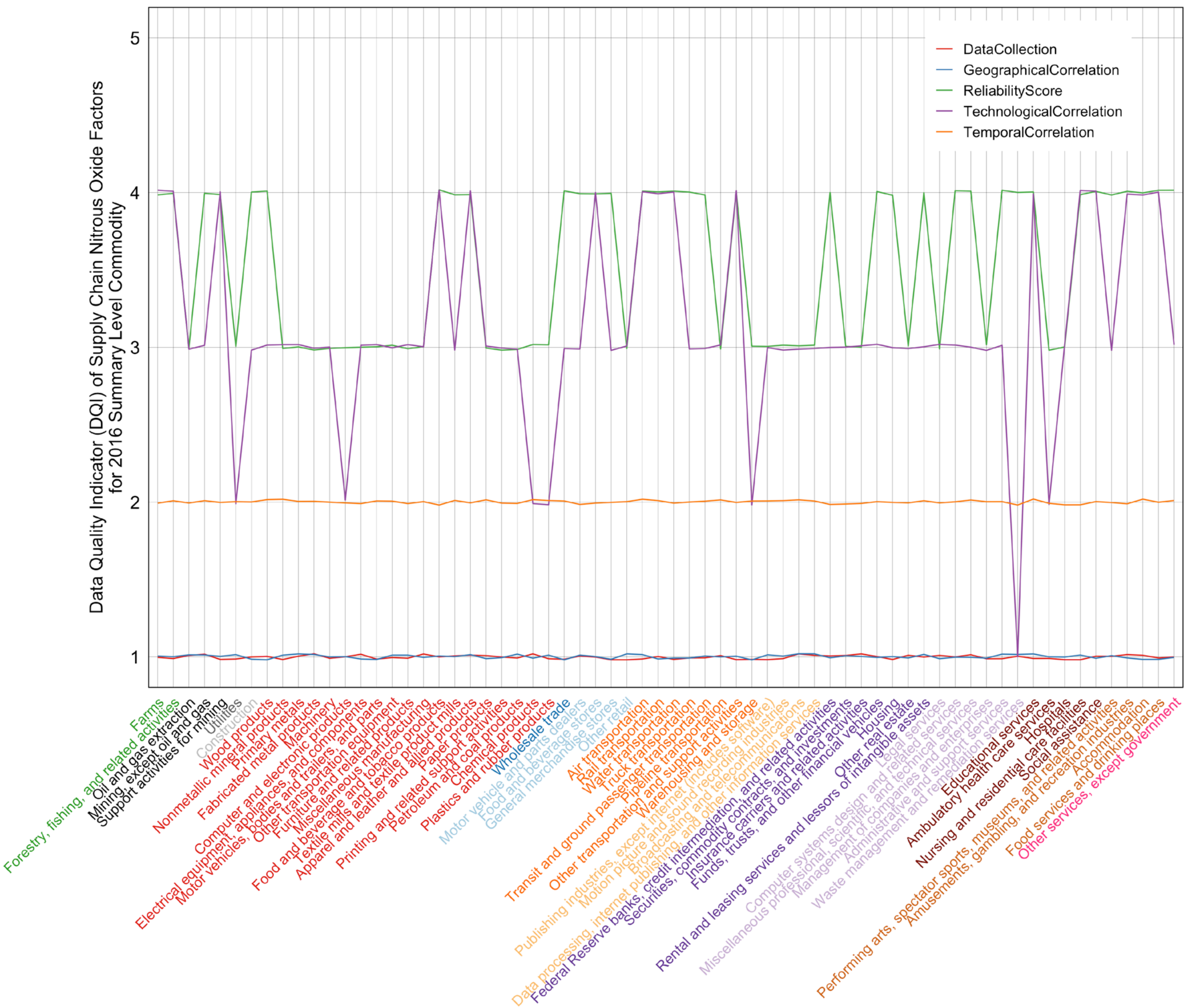


Figure 26: Data quality scores of supply chain N_2O factors for 2016 summary level commodities Data quality assessment scores for all SEFS are provided along with the SEFs in the associated dataset (Ingwersen and Li, 2020).

3.6. Margin Emission Factors

We inspect the relative contribution of margin emissions to the combined supply chain and margin emissions of CO_2, CH_4, and N_2O for 2016 summary commodities in (Figure 24), (Figure 25), (Figure 26). The margin components include transportation, wholesale and retail of commodities. The actual margin requirement $ of margin/$ commodity in producer price by margin components can be found in Appendix 4.

For CO_2, margin emission factors (MEFs) for summary commodities vary from 0 - ~35 kg/$, with the exception of apparel and leather products which has a MEF of ~.71 kg/$. For 66 out of 71 commodities, the contribution of margin emissions to combined supply chain and margin emissions is less than 20%. Apparel and leather products have the largest contribution of 80%. Other manufacturing sectors including computer, furniture, and miscellaneous products have contributions ranging from 30% to 35%.

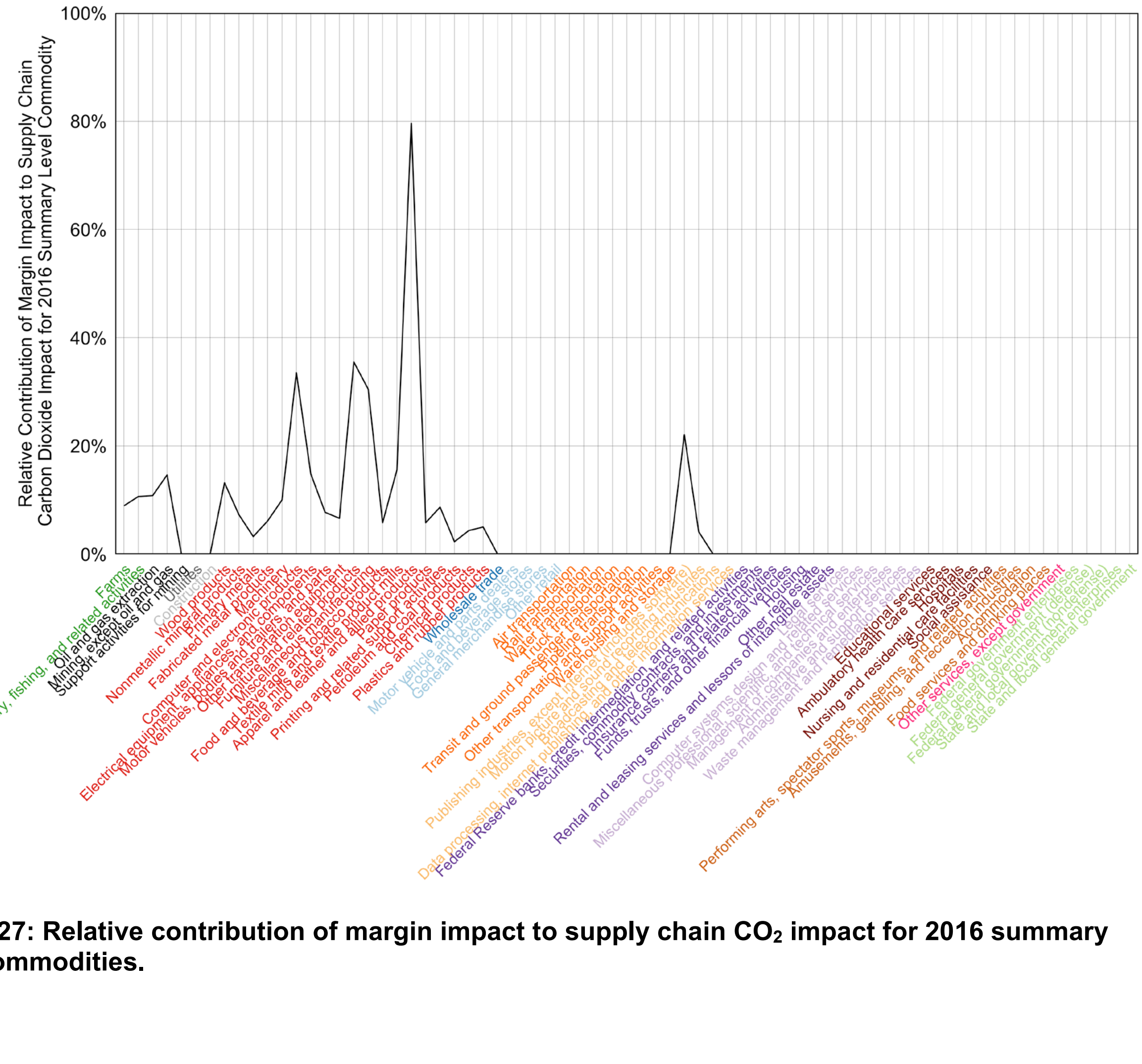


Figure 27: Relative contribution of margin impact to supply chain CO_2 impact for 2016 summary level commodities.

For CH_4, 61 out of 71 commodities, the contribution of margin emissions to combined supply chain and margin emissions of less than 20%. Apparel and leather products have the largest contribution of 79%. Computer and furniture products have contribution of ~55%. Miscellaneous products have contribution of 43%, while publishing industries, except internet (includes software) have contribution of 35%. Other manufactured commodities including electrical, nonmetallic mineral, wood, machinery, and printing products have contribution ranging from 21% to 25%.

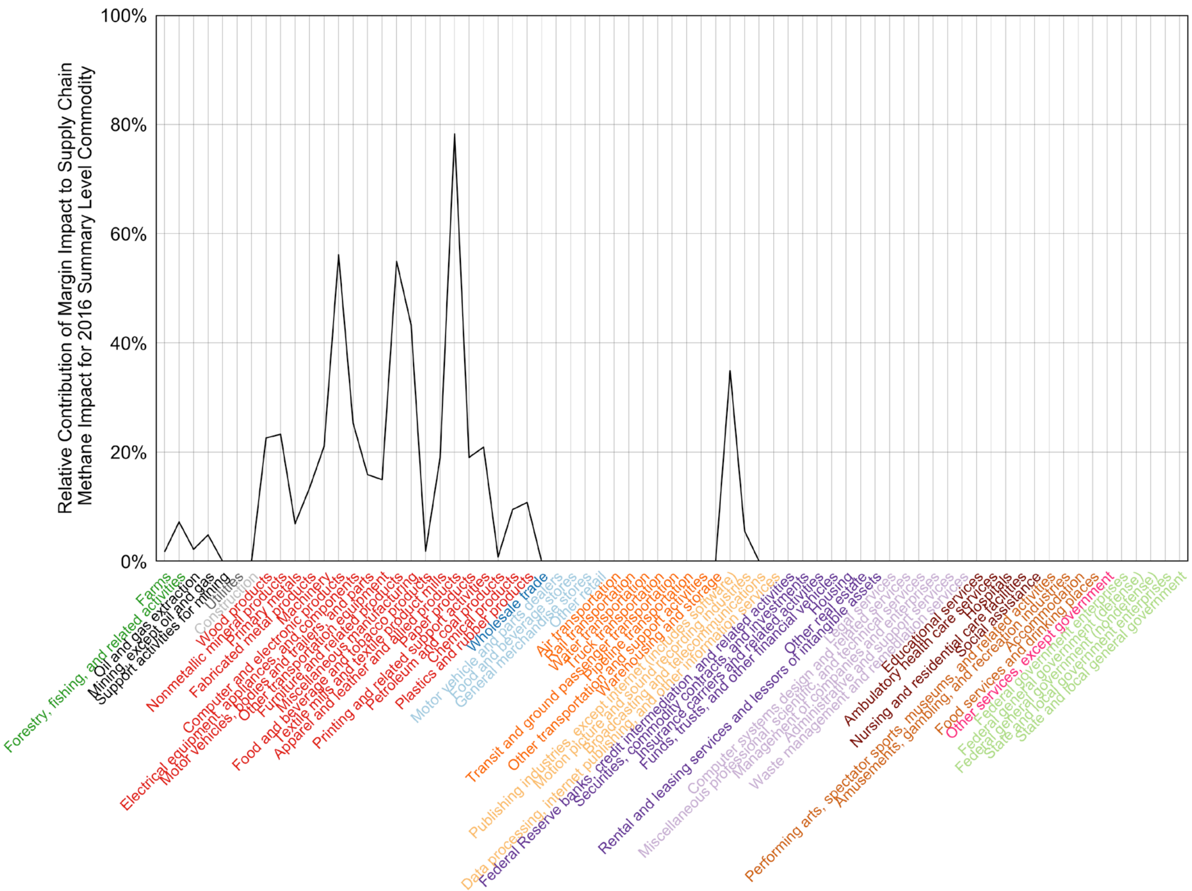


Figure 28: Relative contribution of margin impact to supply chain CH_4 impact for 2016 summary level commodities.

For N_2O, 69 out of 71 commodities have a margin contribution to combined supply chain and margin emissions of less than 20%. Apparel and leather and allied products still have the largest contribution of 42%. Computer products have the second largest contribution of ~24%. Other manufactured commodities including furniture, electrical, miscellaneous, and nonmetallic mineral products have a contribution ranging from 10% to 20%.

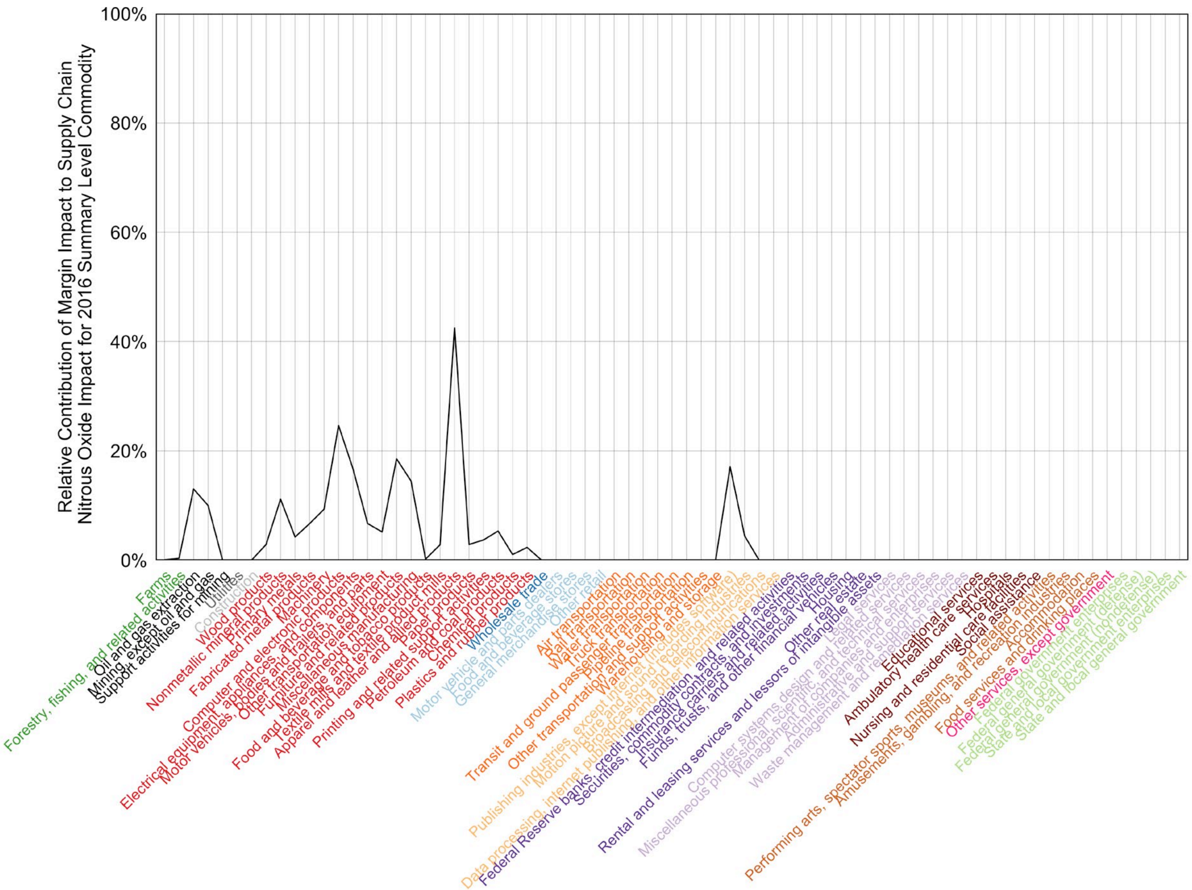


Figure 29: Relative contribution of margin impact to supply chain N_2O impact for 2016 summary level commodities.

4. Discussion

Supply chain emission factors for commodities and industries were calculated with USEEIO models for a series of recent years (2010-2016), for two IO model forms, and for three resolutions of sectoral detail. The intermediate steps in preparation of these factors as well as the final factors have yielded a number of insights.

Overall a decrease occurs in SEFs for primary GHGs from 2010 to 2016 with intermittent fluctuation in the years in between. This can frequently be explained by the increase in economic output (Figure 7), or decreases in emissions for important sectors contributors to supply chain factors, like the decrease in CO_2 emissions for utilities influence is seen on manufacturing CO_2 SEFs in Figure 15. This can also be explained in some cases by sectors becoming more economically-efficient and having less economic requirements in their supply chain (Table 11). This latter change is only evident in models using annual input-output tables at the summary level, and not the detail level.

Differences in SEFs across sectors are generally larger than interannual variation within a sector. In other words, sector rankings of factors were not likely to shift dramatically, if at all, from year to year during this study period. But the relative change within a commodity or industry supply chain factor from year to year can be significant relative to itself. For selected commodities this change is very significant, with commodities have >50% decreases over the time period studied here (see the Appendix 6 tables 'Annual percent change in supply chain factors'). This strong relative change makes the selection of the year important, and suggests the need for regular updates of emission factors.

For the vast majority of commodities and industries, indirect emissions are larger than direct emissions (Figure 12, Figure 13, and Figure 14). Exceptions occur for a few primary sectors, transportation (for CO_2) and waste management (for CH_4). Therefore, the supply chain becomes very important to incorporate and to model comprehensively. Models of the type used here (EEIO models) are the most comprehensive, in terms of including all possible contributors to a supply chain, and superior over process-based models in this respect of capturing the most complete supply chain (Lenzen, 2000).

Industry-based and commodity-based SEFs are very similar for most sectors, but differ widely for a few sectors, including utilities, transportation sectors using various modes, non-farm agricultural activities, and mining support, because these commodities are provided by various industries with differing supply chain emissions, such that the commodity supply chain emissions do not match the supply chain emissions for the industry with the same name. Care should thus be taken in determining whether the commodity or industry factor is most appropriate when selecting the factors for these sectors.

The summary level factors are subject to greater aggregation error than the detailed level factors due to the aggregation of transactions in the input-output tables (Steen-Olsen et al., 2014). For example, if the cement industry is purchasing limestone, at the detail level this is reflected in the Use table in the input of 'stone mining and quarrying' (212310) into 'cement manufacturing' (327310). At the summary level, the cement industry is part of 'monmetallic mineral products'

(327) and this purchase would be reflected in the input of mining, except oil and gas (212) into 'nonmetallic mineral products'. Thus the aggregation the cement sector into 'Nonmetallic mineral products' would reflect purchases of many industries with potentially different environmental characteristics, and the aggregation of limestone to 'Mining, except oil and gas', which represents a broad set of mining commodities, would carry with it a wide environmental profile of mining and not just that of sand mining. This type of aggregation can propagate through the supply chain as well. On the other hand, at the detail level, the economic transaction data reflect older conditions (2012 for 2010-2016 models here), both in the recipes for commodity production in the Use table, and in the industry contribution to commodity output in the Make table. The consequence of using this static economic data appears as the slight departure of the total demand-scaled SEFs and national GHG totals in the validation result (see Appendix 2). Therefore, these tradeoffs must be weighed and considered in the selection of factors used for supply chain emission accounting.

Factors at both summary and detail sector levels provide only an average of commodity or industry performance based on US production. Differentiation with the sector categories is not captured within these factors. These include differences in production technology and practices, environmental controls, scale of production, and location within the United States. For example, the 'Beef cattle ranching and farming' industry SEF would include both a large corporate feedlot operation in Texas producing conventional beef and a small family-owned ranch in Minnesota producing certified-organic beef. To develop factors that distinguish between commodities or industries within a sector, additional data and models would be required.

The results from the National GHG Industry Attribution model that are used by the USEEIO models to create the SEFs have limitations. When data are not originally reported at a detailed level and physical data (like energy use) are not available for allocation at the level of resolution to estimated detailed industry emissions, industry purchases (generally of fuels where emissions are related to fuel combustion) from the 2012 BEA use table are used. Energy purchases could vary across the years for which the data are used. GHG Allocation using purchases is subject to some of the same limitations as the IO data in general. For manufacturing industries, the 2014 MECS survey is used to provide physical fuel use data for the model in the most recent years, because this survey only is available every four years. Further, the MECS resolution is somewhat less than BEA detail resolution. These limitations are reflected in the supply chain factor technological correlation data quality scores available alongside the final factors (Ingwersen and Li, 2020).

The margin emission factors (MEFs) provide coverage of emissions between the production of a commodity and its final sale. The MEFs generally are less than 20% of supply chain emissions but are much higher for a few commodities and have been demonstrated here to not be insignificant. MEFs may be useful for more complete commodity and industry GHG accounting. The MEFs have some limitations due to economic margin data only being available for 2012, and actual margin components not provided by specific subsectors corresponding to the model (e.g., transportation is not divided into truck vs rail vs air transportation), and therefore a similar mix of modes was be assumed for all industries and commodities based on the total. A formal data quality assessment of the MEFs was beyond the scope of this study.

Users of these factors should be cognizant that these factors are only useful for identifying and quantifying potential supply chain GHG emissions. These factors do not cover other types of environmental and human health issues that may be present in the supply chain of goods and services, and actions taken to mitigate GHG emissions in the supply chain can potentially create or augment other issues. Other USEEIO models provide indicators covering a much broader suite of these potential impacts. Please see more on the USEEIO model for availability of the indicators for other potential issues and model applications where the full spectrum of indicators are included, such as the Sustainable Materials Management Prioritization Tools.

4.1. Future Improvements

Studies have revealed that use of the domestic technology assumption, which is how imports are frequently handled in single-region EEIO models, can result in errors in supply chain accounting (Andrew et al., 2009; Lenzen et al., 2004). Inclusion of modeling of other regions, particularly those of major import partners, would likely improve the accuracy of the supply chain emission factors. The detailed level supply chain factors are limited by the release of updated IO table data, for which 2012 data were just released in late 2018. This issue has been acknowledged (Planting and Guo, 2004), and in this case would lead to more timely factors at a higher level of sectoral detail. The National GHG Industry Attribution model could be improved with better data for allocation of emissions to industries in the case that allocation is required. Ultimately the more the IO data and associated environmental data can be disaggregated into more specific industries and commodities, the more accurate the SEFs will become.

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6. Appendices

The following appendices are available as separate documents:

Appendix 1 - Model Equations

Appendix 2 - USEEIO Model Descriptions

Appendix 3 - Industry and Commodity Reference Lists

Appendix 4 - Distribution, Wholesale and Retail Margins for Industries and Commodities

Appendix 5 - National Level Gross Output and Direct Emission Trends

Appendix 6 - Annual Change in Supply Chain Emission Factors

Appendix 7 - Contribution Analysis for Supply Chain Emissions

Appendix 8 - Comparing Summary and Detail Level Direct and Supply Chain Emission Factors

Appendix 9 - Comparing Commodity-based and Industry-based Supply Chain Emission Factors at the Detail Level

Appendix 10 - Model Validation Results

7. Glossary

Term	Definition
Commodity	A term used broadly to refer to goods and services produced by industries in an economy. A given commodity can be produced by more than one industry.
Industry	A term used broadly to refer to sectors that produce goods and services in an economy. A given industry can produce more than one commodity.
Environmentally-extended input-output (EEIO)	A model that links economic input-output tables with environmental data and can be used for environmental assessment of supply chains of industries or commodities, as performed in life cycle assessment.
Direct emission factor (DEF)	Direct GHG emissions from production of a commodity or industry in US (kg)/Economic output of that commodity in the US ($). Economic output reflects the production activity of a given commodity. An example of a direct emission for industry *A* is combustion emissions from a boiler in an industry *A's* facility.
Indirect emission	GHG emission from the supply chain of a commodity or industry derived from purchases of a commodity from an industry generating the emission. An example of a indirect emission for industry *A* is emissions from producing commodity *B* that is purchased by industry *A*.
Supply chain emission factor (SEF)	EEIO-based direct and indirect GHG emissions associated with production of commodity in US from cradle to the point of production(kg)/Economic output of that commodity in the US ($). Also known as 'cradle-to-gate' emission factors (WBCSD, 2013).
Purchaser price	The price paid by the consumer. This is the producer prices plus any associated margin, which generally include distribution, wholesale and retail costs.
Producer price	The cost of production per dollar of output.
Direct requirements	The direct purchases of commodities required to make a dollar output of the commodity or industry of interest. This is also called a recipe.
Total requirements	The direct and indirect purchases of commodities required to make a dollar output of the commodity or industry of interest.
Margin	The difference in the purchaser and producer price for a given commodity.
Sector level	The most aggregated (lowest resolution) categorization of commodities and industries provided by BEA in annual IO tables. The most recent categorization at this level divides the US economy into 15 industries and 17 commodities.
Summary level	A categorization of commodities and industries with a medium resolution provided by BEA in annual IO tables. The most recent

	categorization at this level divides the US economy into 71 industries and 73 commodities.
Detail level	The most resolved categorization of commodities and industries provided by BEA in IO tables produced for 1 in every 5 years, corresponding with the US industry census. The most recent categorization at this level divides the US economy into 405 industries and 405 commodities.
Other GHGs	A grouping of GHGs not including the CO_2, CH_4, and N_2O. These include all other GHGs reporting in the US GHG Inventory, including CFCs, HFCs, NF_3, and SF_6.
Satellite table	A table associated with the primary economic input-output tables that provides additional information, such as environmental emissions, that can be used to support direct and indirect calculation of those emissions associated with the sectors in the input-output tables.

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