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Measuring the Agricultural Supply Chain: Output, Value Added, Employment, and Payroll From Firms Upstream of Farms

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Abstract

U.S. agricultural production relies on a wide array of inputs. Identifying the industries that contribute to the production of these inputs and quantifying the activity that supports the agricultural supply chain provides a more comprehensive accounting of the total contribution of the agricultural supply chain to the U.S. economy. Using input-output (I/O) analysis with 2017 data, we find that economic activity upstream of agricultural production is associated with $570 billion in output value ($515 billion domestically), $241 billion in value added, $119 billion in payroll, and more than 1.5 million jobs. We also identify the commodities that are the most important contributors to upstream agricultural activity, which can inform future research efforts to identify the potential sources of productivity growth in domestic agricultural production and document the spatial distribution of economic activity in the agricultural supply chain.

Keywords: Agricultural supply chain, value added, input/output, agricultural inputs

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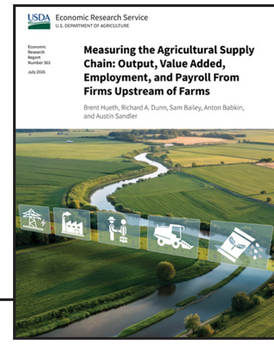

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Key Points

- Agricultural producers use inputs from a range of sectors such as seed, fertilizer, tractors, and feed. Each of the producers of these goods and services have their own input requirements. We define all the stages of production in the agricultural chain that ultimately generate the inputs bought by U.S. farmers and ranchers as “upstream agricultural activity.”
- Upstream agricultural activity contributes more to U.S. Gross Domestic Product (GDP), employment, and compensation to workers than agricultural production itself.
- In 2017, upstream agricultural activity accounted for $570 billion in economic activity measured in output value and $241 billion in value added contributed to U.S. GDP. As a comparison, the value of output from U.S. farms was $423.3 billion, which contributed $156 billion of value added to the Nation’s GDP that year.
- Upstream agricultural activities supported more than 1.56 million jobs in the United States or 1.28 percent of all private sector jobs in the U.S. economy. For comparison, 0.88 percent of all private sector jobs were in agriculture, fishing, and forestry industries. Further, the value of employee compensation associated with upstream activities, $118.7 billion, was nearly three times the $40 billion in employee compensation specifically on farms and ranches.
- Domestic operations accounted for almost $515 billion (92 percent) of the output value upstream of agricultural producers in the agricultural supply chain with imports making up the rest.

Why Does This Matter?

The production of agricultural commodities requires goods and services (called inputs) from a wide array of industries, including construction, manufacturing, wholesale and retail trade, transportation, professional and business services, and energy. The production of each of these inputs has its own set of input requirements. Identifying the industries that support domestic agricultural production and calculating the value of the activities they undertake inform several areas of interest to policy makers, researchers, and business leaders. First, accounting for upstream agricultural activity gives a more complete picture of the total contribution of domestic agriculture to the U.S. economy. Second, identifying the industries engaged in upstream agricultural activity can better establish the places (both rural and urban) where local economies are integrated into the agricultural supply chain. Finally, identifying these industries also highlights possible sources of total factor productivity growth in agricultural production. USDA, Economic Research Service continues to be one of the leading sources of statistics on the contribution of the agricultural supply chain to the U.S. economy, and this work complements existing efforts by estimating the value of output, value added, employee compensation, and employment associated with activity upstream of agricultural producers.

A Few More Details

- Decomposing the $515 billion in domestic upstream agricultural activity and associated $241 billion in value added by supply chain position, the direct use of domestically produced inputs by U.S. agricultural producers accounted for about 57 percent ($294 billion) of output value, 54 percent ($131 billion) of value added, 51 percent ($61 billion) of payroll, and 57 percent (889 thousand) of all jobs.
- The remaining $221 billion in output value, $110 billion in value added, $58 billion in compensation, and 673,000 jobs arise from linkages further back in the agricultural supply chain, such as the value of chemicals used by pesticide producers and steel used by farm machinery manufacturers.
- Decomposing domestic upstream agricultural activity by product type, production of non-agricultural commodities accounted for the majority of activity, generating about $425 billion in total output, $213 billion in value added, $113 billion in payroll, and 1.47 million jobs.
- Domestic production of agricultural commodities that were used either directly or indirectly by other domestic agricultural producers accounted for the remaining $90 billion in total output, $28 billion in value added, $6 billion in payroll, and 96,000 jobs.
- The largest non-agricultural contributors to upstream agricultural activity were support services for agriculture and forestry, animal food manufacturing, real estate services, farm machinery and equipment manufacturing, non-residential construction, pesticide and agricultural chemical manufacturing, petroleum refining, scientific research and development, insurance carriers, non-durable good wholesalers, and transportation services.

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Measuring the Agricultural Supply Chain: Output, Value Added, Employment, and Payroll From Firms Upstream of Farms

Introduction

Production activities on U.S. farms contribute about 0.8 percent of all value added in the U.S. economy (Zahniser & Kassel, 2024). But farms are just one link within the larger agricultural supply chain that extends both upstream and downstream of the farm gate (U.S. Department of Agriculture (USDA), 2022). Upstream of agricultural producers are all the production and trade activities that ultimately provide the inputs used by farm and ranch operations, while downstream includes all the activities between the agricultural producer and final consumers.

Available data suggest that the total contribution of agricultural production to the U.S. economy through its purchase of inputs, and the value added as agricultural products are transformed into new products by other businesses, is significantly larger than the contribution from on-farm production (Kassel et al., 2024; Zeng & Dong, 2022). And, of every dollar spent by U.S. consumers on food, about 92 percent of value added was provided by non-farm businesses in the agricultural supply chain (USDA, Economic Research Service (ERS), 2023).

USDA, ERS has a long history of measuring the contribution of activity within the agricultural supply chain to the U.S. economy (Lee et al., 1987; Edmondson et al., 1995) and continues to provide the most detailed estimates of activity in the agricultural supply chain at the national level through several data products addressing different dimensions of its contribution (see box "Current USDA, ERS Efforts to Measure the Agricultural Supply Chain" for descriptions of these USDA, ERS data products and their coverage of upstream activity). This report complements these efforts by applying methods specifically designed to quantify activity upstream of designated sectors to document the contribution of agricultural production to the U.S. economy through its demand for production inputs.

Existing USDA, ERS products focus on the economic implications of demand-side effects arising from the sale of domestically produced agriculture, food, and fiber products to domestic or foreign purchasers. This report introduces a supply-side perspective that measures the effect of economic linkages backward from the farm gate. By expanding the existing USDA, ERS portfolio to include complete coverage of activity in the agricultural chain upstream of agricultural producers, this report fills two gaps in reporting on agricultural industries and sources of productivity growth in the sector.

First, domestic agricultural production depends on inputs across a variety of industries including construction, manufacturing, wholesale and retail trade, transportation, professional and business services, and energy (USDA, 2022). Each of the businesses producing goods and services used by agricultural operations have their own set of input requirements that similarly span multiple industries. Through this web of upstream supply chain linkages, domestic agricultural producers support the creation of economic value added, jobs, and worker salaries. The addition of these estimates to the existing literature further advances the aim of accurately measuring the total contribution of agricultural production to the U.S. economy.

Second, the growth in agricultural total factor productivity (TFP) is well documented (Wang et al., 2022a). Over the past seven decades, agricultural output has grown while inputs have remained flat (Wang et al., 2022b). Determining the mechanisms that have driven past TFP growth can inform researchers and policymakers about potential areas to support continued productivity growth. Identifying the industries in the agricultural supply chain upstream of agricultural producers that are the most important sources of output and value added is a key step in this process.

To quantify upstream agricultural activity, we apply a standard tool from input-output (I/O) analysis to data published by the U.S. Department of Commerce, Bureau of Economic Analysis (BEA) that summarizes economic activity across industries and commodities to estimate the value of output, value added, employee compensation, and employment associated with economic activity upstream of agricultural producers in the agricultural supply chain. These estimates directly support a more comprehensive accounting of the total contribution of the agricultural supply chain to the U.S. economy.

In addition to economy-wide estimates of upstream activity, we also present a collection of decompositions. These are intended to more finely document how different sectors of the economy contribute to the agricultural supply chain, and thereby serve as a foundation for further identifying the potential sources of TFP growth and the spatial distribution of the agricultural supply chain:

- Agricultural commodities can be inputs to other agricultural producers (e.g., seeds planted by farmers, grains in animal feed, calves to feedlots). As a result, some of the activity upstream of one agricultural operator may include production at other agricultural operations. Therefore, we separately estimate activity upstream of agricultural production into that associated with agricultural commodities and that associated with non-agricultural commodities.
- Recognizing that the agricultural supply chain extends several links in both directions from the farm gate, we also decompose measures of economic activity into direct and indirect components. The direct component captures the use of inputs in the production of agricultural commodities (e.g., the fertilizer used by soybean farmers, the combines used by wheat farmers, the feed used by egg farmers). The indirect component captures economic activity farther upstream from the farm gate (e.g., the chemicals used by fertilizer manufacturers, the research and development used by chemical manufacturers, the steel used by machinery manufacturers).
- Some inputs are transformed or exhausted during production (intermediate inputs) such as seed, fertilizer, and fuel. Other inputs (capital inputs) remain for use in subsequent production cycles, such as combines, tractor trailers, factories, and farm buildings. We decompose the contribution of intermediates separate from the contribution of capital.
- Finally, we identify the broad sectors and detailed commodities that contribute the greatest share of output value upstream of agricultural producers.

Current USDA, ERS Efforts to Measure the Agricultural Supply Chain

USDA, Economic Research Service (ERS) has three extant products that report on at least one component of economic activity in the agricultural supply chain upstream of the farm gate, each using data or methods related to those applied in this report.

Agricultural and Food Statistics: Charting the Essentials: The *Agriculture and Food Statistics: Charting the Essentials* data product is a collection of charts and maps presenting key statistics on the farm and food sectors of the economy, including agricultural markets and trade, farm income, food prices and consumption, food security, rural economies, and the interaction of agriculture and natural resources (Kassel et al., 2024). Recognizing that the U.S. agricultural sector extends beyond the farm business, a component of *Charting the Essentials* is the *Ag and Food Sectors and the Economy* series, which reports the value added to U.S. Gross Domestic Product and employment by agricultural and selected related industries. Although some activity included in these industries occurs upstream of agricultural production, many important activities are omitted (e.g., pesticide, fertilizer, and farm equipment machinery manufacturing). Further, none of the selected industries are exclusively upstream of agricultural operations, for example the food manufacturing sector includes both the production of animal feed (upstream) and food consumed by households (downstream).

Agricultural Trade Multipliers: The *Agricultural Trade Multipliers* (ATM) product provides annual estimates of employment and output in the U.S. economy associated with international trade in farm and food products (Zeng et al., 2024). A key feature of this product is its accounting for both direct and indirect contributions through supply chain linkages across different sectors of the economy. The ATM product focuses on value and employment from international trade, and therefore its estimates are only constructed for traded amounts, not the entirety of domestic use in agricultural production. Further, ATM provides an estimate of the total contribution by industry, not separate estimates for contributions arising upstream and downstream of agricultural producers.

Food Dollar Series: The *Food Dollar Series* product reports an industry series that allocates every dollar of consumer spending on domestically produced food to the various industries involved in the food supply chain (Canning, 2011; Baker & Zachary, 2023; Baker & Zachary, 2026). The industries that are predominantly associated with contributing inputs to agricultural producers are termed agribusiness. Although the agribusiness industry grouping includes many of the most important inputs to agricultural production, there is activity within these industries that occurs downstream of agricultural producers and there are industries assigned to other categories that are active upstream of the farm gate. Further, because the focus of the Food Dollar Series is consumer spending on food, activity in other value chains that use agriculture or forestry inputs falls outside its scope.

Notational Conventions and Variable Definitions

General notation

$\underbrace{\boldsymbol{Z}}_{rows \times cols}$	Matrices are denoted bold, upper-case font with dimensions in underbrace
z_{ij}	The element from the i^{th} row and j^{th} column of the matrix $\boldsymbol{Z}$
$\boldsymbol{Z}^{-1}$	The inverse of matrix $\boldsymbol{Z}$
$\underbrace{\boldsymbol{Z}}_{rows \times 1}$	Column vectors are denoted bold, lower-case font with dimensions in underbrace
z_i	The i^{th} element from the vector $\boldsymbol{z}$
$\hat{\boldsymbol{z}}$	The diagonal matrix formed by the vector $\boldsymbol{z}$ with $\hat{z}_{ii} = z_i$ and $\hat{z}_{ij} = 0 \; \forall \; i \neq j$
$\mathcal{Z}$	Sets are denoted in script, uppercase font
$\boldsymbol{Z}_{-\mathcal{Z}}$	The matrix $\boldsymbol{Z}$ with the columns associated with the elements of $\mathcal{Z}$ replaced with zeros
$\boldsymbol{I}$	The identity matrix (a diagonal matrix of ones)
$z \longrightarrow z'$	A map of z°to z' so that the elements of z change, but not its type or structure

Variable definitions

$\mathcal{C}$	The set of U.S. Department of Commerce, Bureau of Economic Analysis (BEA) detail-level industries
C	The number of BEA detail-level commodities (the cardinality of $\mathcal{C}$)
c	The commodity index (an element of $\mathcal{C}$)
$\mathcal{N}$	The set of BEA detail-level industries
N	The number of BEA detail-level commodities (the cardinality of $\mathcal{N}$)
n	The commodity index (an element of $\mathcal{N}$)
$\mathcal{A}$	The subset of agricultural commodities ($\mathcal{A} \subset \mathcal{C}$)
$\boldsymbol{q}$	Domestic commodity production vector (dimensions $C \times 1$)
$\boldsymbol{y}$	Domestic industry production vector (dimensions $N \times 1$)
$\boldsymbol{x}$	Intermediate input commodity vector (dimensions $C \times 1$)
$\boldsymbol{k}$	Capital investment commodity vector (dimensions $C \times 1$)
$\boldsymbol{f}$	Final demand commodity vector (dimensions $C \times 1$)
$\boldsymbol{m}$	Import commodity vector (dimensions $C \times 1$)
$\boldsymbol{R}$	Direct requirements matrix (dimensions $C \times C$)
$\square^d / \square^m$	Subset over domestic/imported commodities
$\square^x / \square^k$	Subset over commodities used as intermediates/capital

Methods and Data

To calculate the contribution of agriculture to the domestic economy through its demand for production inputs within an I/O framework, we use the hypothetical extraction method (HEM) to calculate the partial hypothetical extraction backward linkage (PHEB).[1] In this section, we describe the intuition undergirding HEM approaches and present the structure of our analysis. While some mathematical derivations are provided, we leave technical details to the appendix for the interested reader (box "Notational Conventions and Variable Definitions" summarizes the notational conventions and variable definitions used in both the body and appendix of this report).

Hypothetical Extraction Method (HEM)

HEM begins with the canonical I/O specification of domestic economic activity:

$$\underbrace{\boldsymbol{q}}_{C\times 1} = \underbrace{\boldsymbol{L}}_{C\times C}\,\underbrace{\boldsymbol{f}}_{C\times 1} \tag{1}$$

where $\boldsymbol{q}$ is a vector of the domestic production of C commodities, $\boldsymbol{f}$ is a vector of final demand for the C commodities, and $\boldsymbol{L}$ is the Leontief inverse.[2] Final demand includes all possible uses of a commodity except as an input to domestic production (e.g., household purchases of goods, services, and residential housing; some types of government spending; and foreign trade). The Leontief inverse summarizes the relationship between the use of inputs and the production of outputs. Specifically:

$$\boldsymbol{L} = (\boldsymbol{I} - \mathbf{A})^{-1} \tag{2}$$

where $\boldsymbol{I}$ is the $C \times C$ identity matrix and $\boldsymbol{A}$ is the direct input coefficients matrix with elements a_{ij} denoting the expenditure on commodity c_j as an input for every dollar of commodity c_i produced. In its most general formulation, HEM quantifies various economic linkages by simulating a hypothetical economy under alternative assumptions about production ($\boldsymbol{A} \longrightarrow \boldsymbol{A}'$) and final demand ($\boldsymbol{f} \longrightarrow \boldsymbol{f}'$):

$$\Delta = \boldsymbol{q} - \boldsymbol{q}' = \boldsymbol{q} - \boldsymbol{L}'\boldsymbol{f}' = \boldsymbol{q} - (\boldsymbol{I} - \boldsymbol{A}')^{-1}\boldsymbol{f}' \tag{3}$$

where Δ is the vector of commodity output differences relative to observed output.[3]

HEM is an established tool for analyzing economic activity within the I/O framework that continues to be actively applied across a variety of research areas. The earliest implementations of HEM calculated the change in output that would arise if a sector was entirely removed the economy, i.e., neither

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[1] See Miller and Lahr (2001) and Miller and Blair (2009, 2022) for a thorough overview of HEM. Our presentation largely follows Miller and Blair (2009) incorporating notation from Miller and Lahr (2001) and terminology from Miller and Blair (2022).

[2] The Leontief inverse provides the amount of inputs from each sector of the economy that are required to produce one unit of output from each sector. This particular formulation represents a Leontief quantity ("demand-pull") I/O model. The Agricultural Trade Multipliers and Food Dollar Series products published by USDA, ERS are examples of applications that apply multiplier methods within a Leontief quantity model.

[3] Multiplier models can be viewed as a type of hypothetical extraction. If final demand is partitioned into two parts, such that $\boldsymbol{f} = \boldsymbol{f}^1 + \boldsymbol{f}^2$, then the multiplier model calculates the contribution of $\boldsymbol{f}^1$ as:

$$\Delta(\boldsymbol{f}^1) = \boldsymbol{L}\boldsymbol{f}^1$$

Notice that by adding and subtracting $\boldsymbol{q}$ we get the following:

$$\Delta(\boldsymbol{f}^1) = \boldsymbol{q} - \boldsymbol{q} + \boldsymbol{L}\boldsymbol{f}^1 = \boldsymbol{q} - \boldsymbol{L}\boldsymbol{f} + \boldsymbol{L}\boldsymbol{f}^1 = \boldsymbol{q} - \boldsymbol{L}(\boldsymbol{f} - \boldsymbol{f}^1) = \boldsymbol{q} - \boldsymbol{L}\boldsymbol{f}^{-1}$$

So that the result of a multiplier model is equivalent to comparing the observed economy with a hypothetical economy in which some portion of final demand has been extracted. The difference between multiplier models and HEM is thus what elements are subject to removal. The practical implication is that multiplier models are appropriate for questions about the contribution of final demand (consumption), while HEM is appropriate for questions about the contribution of supply (production). Further, both can be interpreted as accounting exercises and not actual counterfactuals about how the economy would respond if input usage or final consumption changed.

produced nor consumed (Paelinck et al., 1965; Strassert, 1968; Schultz, 1976; Schultz, 1977; Meller & Marfán, 1981; Milana, 1985; Heimler, 1991). Responding to various lockdown policies enacted by national and regional governments during the Coronavirus (COVID-19) pandemic, researchers used HEM for precisely this purpose to identify the sectors for which full or partial closures would have the largest economic impacts (Giametti et al., 2020; Haddad et al., 2020, Sanguinet et al., 2021). This specific measure is termed the *complete hypothetical extraction total linkage* and is formulated for a single sector s by replacing the s^{th} column of $\boldsymbol{A}$ with zeroes (e.g., restaurants no longer purchase inputs), the s^{th} row of $\boldsymbol{A}$ with zeroes (restaurants no longer supply inputs to other industries), and s^{th} element of $\boldsymbol{f}$ with zero (households can no longer purchase meals from restaurants). This approach readily generalizes to extracting multiple sectors (the set $\mathcal{S}$) simultaneously by zeroing out all the columns, rows, and elements associated with $s \in \mathcal{S}$.

Since its initial development, the set of linkages defined under HEM has grown to quantify various dimensions of both interindustry (Szyrmer & Walker, 1983; Szyrmer, 1986; Szyrmer, 1992; Groenewold et al., 1993) and interregional connections (Miller & Blair, 1983; Dietzenbacher et al., 1993; Dietzenbacher & van der Linden, 1997) measured in terms of output value, value added, income, and employment. For our application, we calculate the *partial hypothetical extraction backward linkage* (PHEB), which was first presented in publication by Szyrmer and Walker (1983) and later formalized under the HEM umbrella by Lenzen (2003) and Gallego and Lenzen (2005).

PHEB recovers the value of backward linkages from sector s by zeroing out only the s^{th} column of $\boldsymbol{A}$ and recalculating $\boldsymbol{q}$.[4] In other words, it simulates a hypothetical economy where the domestic input demands for sector s have been extracted. Letting $\boldsymbol{A}_{-s}$ denote the direct input coefficients when the s^{th} column of $\boldsymbol{A}$ has been set to zero (and $\boldsymbol{L}_{-s}$ denote the resulting Leontief inverse), the value of the backward linkages from sector s is:

$$\Delta(s) = \boldsymbol{q} - \boldsymbol{q}(s) = \boldsymbol{q} - \boldsymbol{L}_{-s} = \boldsymbol{q} - (\boldsymbol{I} - \boldsymbol{A}_{-s})^{-1}\boldsymbol{f} \qquad (4)$$

A key feature of PHEB is that it captures not only the direct contribution of a sector through the inputs it uses (first-order), but also the (second-order) inputs used to produce the first-order inputs, and the (third-order) inputs used to produce second-order inputs, *ad infinitum* back through the supply chain. In other words, by applying PHEB to agricultural production, we account for the pesticide used by wheat farmers, the chemicals used to produce that pesticide, the mining activity used to produce those chemicals, the accounting firm hired by the mining company, and so forth.

Although PHEB is calculated by simulating a hypothetical economy, it need not be interpreted literally as the prediction of a new equilibrium if a sector truly eliminated its input needs.[5] Much like multiplier models, there are alternative interpretations of HEM that are valid holding prices and production mixes at their observed levels. First, HEM continues to be applied to identify influential sectors of the economy, that is, those sectors for which a marginal increase or decrease in domestic production would have the greatest effect on total activity in the economy (Temurshoev, 2010; Miller & Lahr,

[4] Temurshoev (2010) demonstrates how many HEM linkage calculations simplify to closed-form solutions that can be calculated directly from the elements of the Leontief inverse, rather than constructing a new value of domestic output. This is the basis for the presentation in Miller and Blair (2022). These algebraic results are especially useful if a set of sectors are each removed individually, and the results compared. Our application is the opposite—a large set of commodities that together comprise the agricultural production sector are removed simultaneously. The algebraic results of Temurshoev (2010) do not apply in this case. Therefore, we follow the presentation of Miller and Blair (2009) and Miller and Lahr (2001).

[5] In some applications, the results from HEM are indeed treated as the counterfactual from a proposed policy or disruptive economic shock. While the validity of such an interpretation depends on the plausibility of additional assumptions about potential substitution patterns and price responses, this challenge is not unique to HEM within the I/O framework. For example, analyses that simulate the effect of changes in final demand caused by shocks to consumer expenditure, government spending, or exports using multiplier models face identical challenges to validity.

2011; Temurshoev & Oosterhaven, 2014). Second, HEM is applied as an accounting tool to quantify the contribution of domestic production through its backward and/or forward supply chain linkages, just as multiplier methods calculate the contribution of different sectors through final demand channels.[6] This is perhaps the most active contemporary use of HEM and recent applications have embedded HEM into total flow and social accounting methods (Los & Timmer, 2018) to assign sectoral contributions to a greater range of measures, including natural resource usage (Duarte et al., 2002; Lenzen, 2003), emissions (Wang et al., 2013; Ali, 2015; Zhao et al., 2015; Hanaka et al., 2017; Tokiko, 2018; Hanaka et al., 2022), and environmental externalities (Beaufils et al., 2022). PHEB calculations for agricultural production presented in this report fall under this latter interpretation as we account for its contribution to output value, value added, worker compensation, and employment in the U.S. economy through the demand for intermediate and capital inputs produced domestically and imported.

Specifying the PHEB

Equation (4) is a generic formulation of PHEB. To decompose PHEB separately by source (domestic versus imported) and type (intermediate inputs versus capital), the I/O relationships equating supply and use must be further specified.

The domestic supply-use relationship over commodities is specified as:

$$\underbrace{\boldsymbol{q}}_{C\times 1} = \underbrace{\boldsymbol{x}^d}_{C\times 1} + \underbrace{\boldsymbol{k}^d}_{C\times 1} + \underbrace{\boldsymbol{f}^d}_{C\times 1} \tag{5}$$

where domestic commodity output is allocated to either intermediate inputs used by domestic producers ($\boldsymbol{x}^d$), private capital used by domestic producers ($\boldsymbol{k}^d$), or final demand ($\boldsymbol{f}^d$). Final demand includes all other uses of commodities (e.g., household consumption and residential investment, government consumption and investment, exports, and changes in inventory).

Define the domestic intermediate input direct requirements matrix as $\boldsymbol{R}^{dx}$ with elements r_{ij}^{dx} that equal the amount of commodity i that is needed as an intermediate input to produce one unit of commodity j. Analogously, define the domestic capital input direct requirements matrix as $\boldsymbol{R}^{dk}$. Then, we can re-express (5) as:

$$\underbrace{\boldsymbol{q}}_{C\times 1} = (\underbrace{\boldsymbol{R}^{dx}}_{C\times C} + \underbrace{\boldsymbol{R}^{dk}}_{C\times C})\boldsymbol{q} + \underbrace{\boldsymbol{f}^d}_{C\times 1} = \underbrace{\boldsymbol{A}^d}_{C\times C}\,\boldsymbol{q} + \boldsymbol{f}^d \tag{6}$$

Rearranging yields:

$$\boldsymbol{q} = (\underbrace{\boldsymbol{I}}_{C\times C} - \underbrace{\boldsymbol{A}^d}_{C\times C})^{-1}\boldsymbol{f}^d = \underbrace{\boldsymbol{L}^d}_{C\times C}\,\boldsymbol{f}^d \tag{7}$$

which has the same structure to equation (1).

The supply-use equation for imported commodities is similarly defined:

$$\underbrace{\boldsymbol{m}}_{C\times 1} = \underbrace{\boldsymbol{x}^m}_{C\times 1} + \underbrace{\boldsymbol{k}^m}_{C\times 1} + \underbrace{\boldsymbol{f}^m}_{C\times 1} \tag{8}$$

[6] The Agricultural Trade Multipliers and Food Dollar Series are examples of USDA, ERS products using multiplier models as accounting tools for the contribution of exports and consumer expenditure on food.

where $\boldsymbol{m}$ is the vector of commodity imports which is allocated to intermediate inputs used by domestic producers ($\boldsymbol{x}^m$), private capital used by domestic producers ($\boldsymbol{k}^m$), or final demand ($\boldsymbol{f}^m$). Letting $\boldsymbol{R}^{mx}$ and $\boldsymbol{R}^{mk}$ denote the imported direct input requirement and imported direct capital requirements matrices and substituting yields:

$$\boldsymbol{m} = \underbrace{\boldsymbol{R}^{mx}}_{C\times C}\boldsymbol{q} + \underbrace{\boldsymbol{R}^{mk}}_{C\times C}\boldsymbol{q} + \boldsymbol{f}^m \tag{9}$$

Defining Agricultural Production

Table 1 identifies the set of 12 commodities/industries included in the category of agricultural production in this application, denoted $\mathcal{A}$. This set includes all BEA detail-level industries that cover the two-digit NAICS sector Agriculture, Forestry, Fishing, and Hunting, except for Support Activities for Agriculture and Forestry (115000). We include Forestry and logging because this activity often occurs in National Forests, which are administered by USDA, Forest Service. This inclusion is also consistent with the reporting on trade in lumber and wood products as part of the Agricultural Trade Multipliers data product. We include Fishing, hunting, and trapping as wild caught fish, animals, and plants are part of the domestic food supply. This inclusion is consistent with the trade of wild-caught seafood being included in the Agricultural Trade Multipliers data product and the purchase of wild-caught seafood by households being included in the Food Dollar Series data product.

Table 1
U.S. Department of Commerce, Bureau of Economic Analysis (BEA) detail-level commodities/industries included in agricultural production

Code	Industry/commodity title
1111A0	Oilseed farming
1111B0	Grain farming
111200	Vegetable and melon farming
111300	Fruit and tree nut farming
111400	Greenhouse, nursery, and floriculture production
111900	Other crop farming
1121A0	Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming
112120	Dairy cattle and milk production
112A00	Animal production, except cattle and poultry and eggs
112300	Poultry and egg production
113000	Forestry and logging
114000	Fishing, hunting and trapping

Source: USDA, Economic Research Service.

Calculating the PHEB

Recovering the PHEB of the 12 commodities in $\mathcal{A}$ begins with calculating the domestic component. First, replace $\boldsymbol{R}^{dx}$ and $\boldsymbol{R}^{dk}$ in equation (6) with their extracted counterparts (i.e., the elements within the 12 columns associated with these commodities that are replaced with zeros). Denote the resulting agriculture-extracted requirements matrices $\boldsymbol{R}^{dm}_{-\mathcal{A}}$ and $\boldsymbol{R}^{dk}_{-\mathcal{A}}$ so that:

$$\boldsymbol{A}^d_{-\mathcal{A}} = \boldsymbol{R}^{dx}_{-\mathcal{A}} + \boldsymbol{R}^{dk}_{-\mathcal{A}}, \qquad \boldsymbol{L}^d_{-\mathcal{A}} = (\boldsymbol{I} - \boldsymbol{A}^d_{-\mathcal{A}})^{-1} \tag{10}$$

The domestic PHEB is calculated as in equation (4):

$$\underbrace{\Delta^{q}(\mathcal{A})}_{C\times 1} = \underbrace{\boldsymbol{q}}_{C\times 1} - \underbrace{\boldsymbol{q}(\mathcal{A})}_{C\times 1} = \underbrace{\boldsymbol{q}}_{C\times 1} - \underbrace{\boldsymbol{L}^{d}_{-\mathcal{A}}}_{C\times C} \underbrace{\boldsymbol{f}^{d}}_{C\times 1} \tag{11}$$

The c^{th} element of $\Delta^{q}(\mathcal{A})$ provides the value of the output of commodity c that is upstream of agricultural production. The total domestic PHEB is calculated by summing over every element of the vector, while aggregations over commodity groups (agricultural, manufacturing, construction, etc.) can be constructed by summing over the appropriately defined subsets.

Notice from equation (5), if $\boldsymbol{q}$ changes on the left side of the equality, then to maintain balance $\boldsymbol{x}^{d}$ and $\boldsymbol{k}^{k}$ must together change by the same amount because $\boldsymbol{f}^{d}$ is taken as fixed. To allocate $\Delta^{q}(\mathcal{A})$ between intermediate and capital inputs, define the $C \times 1$ vector $\tilde{\boldsymbol{q}}$ with elements:

$$\tilde{q}_{c} = \begin{cases} q_{c} & if\ c \in \mathcal{A} \\ q(\mathcal{A})_{c} & if\ c \notin \mathcal{A} \end{cases} \tag{12}$$

The domestic PHEB is then decomposed between intermediate and capital inputs by:

$$\underbrace{\Delta^{q}(\mathcal{A})}_{C\times 1} = \Delta^{dx}(\mathcal{A}) + \Delta^{dk}(\mathcal{A}) = \underbrace{\boldsymbol{R}^{dx}_{-\mathcal{A}}}_{C\times C} \underbrace{\tilde{\boldsymbol{q}}}_{C\times 1} + \underbrace{\boldsymbol{R}^{dk}_{-\mathcal{A}}}_{C\times C} \underbrace{\tilde{\boldsymbol{q}}}_{C\times 1} \tag{13}$$

Applying similar logic, the import component of PHEB is decomposed by:

$$\underbrace{\Delta^{m}(\mathcal{A})}_{C\times 1} = \Delta^{mx}(\mathcal{A}) + \Delta^{mk}(\mathcal{A}) = \boldsymbol{R}^{mx}_{-\mathcal{A}}\tilde{\boldsymbol{q}} + \boldsymbol{R}^{mk}_{-\mathcal{A}}\tilde{\boldsymbol{q}} \tag{14}$$

Direct and Indirect Linkage

It is possible to further decompose the PHEB results into direct and indirect components. The direct component captures the use of intermediate and capital inputs in the production of agricultural commodities (first-order), while the indirect component captures the use of intermediate and capital inputs in all of the preceding steps in the supply of the first-order inputs (second-order and above). Define the $C \times 1$ vectors $\tilde{\boldsymbol{q}}^{\mathcal{A}}$ and $\tilde{\boldsymbol{q}}^{-\mathcal{A}}$ such that:

$$\tilde{q}^{\mathcal{A}}_{c} = \begin{cases} q_{c} & if\ c \in \mathcal{A} \\ 0 & if\ c \notin \mathcal{A} \end{cases}, \qquad \tilde{q}^{-\mathcal{A}}_{c} = \begin{cases} 0 & if\ c \in \mathcal{A} \\ q(\mathcal{A})_{c} & if\ c \notin \mathcal{A} \end{cases} \tag{15}$$

Noting that $\tilde{\boldsymbol{q}} = \tilde{\boldsymbol{q}}^{\mathcal{A}} + \tilde{\boldsymbol{q}}^{-\mathcal{A}}$, the domestic PHEB is decomposed into direct and indirect components by substituting $\tilde{\boldsymbol{q}}$ in equation (13) with $\tilde{\boldsymbol{q}}^{\mathcal{A}}$ and $\tilde{\boldsymbol{q}}^{-\mathcal{A}}$, respectively. The intuition for the former is that multiplying the domestic requirements matrices by the observed production of agricultural commodities while zeroing out the production of non-agricultural commodities yields the input usage by agricultural commodity producers. The latter substitution returns the change in input usage from the production of non-agricultural commodities that are upstream of agricultural commodity production. The import PHEB is decomposed similarly by substituting $\tilde{\boldsymbol{q}}$ in equation (14) with $\tilde{\boldsymbol{q}}^{\mathcal{A}}$ and $\tilde{\boldsymbol{q}}^{-\mathcal{A}}$.

Value Added, Worker Compensation, and Employment

As presented, PHEB recovers the value of domestic output upstream of agricultural production in the supply chain. Changes in gross output are generally less informative about real economic impact than value added (output minus intermediate input costs), worker compensation, and employment (Miller & Blair, 2022). Define the value added coefficient vector $\boldsymbol{\pi}^{v\alpha}$ with elements $\pi_c^{v\alpha}$ that equal the value added per dollar of commodity c produced in the economy (see the appendix for details on its construction). The PHEB measured in output can be translated to value added terms:

$$\underbrace{\Delta^{va}(\mathcal{A})}_{C\times 1} = \underbrace{\widehat{\boldsymbol{\pi}}^{va}}_{C\times C} \underbrace{\Delta^{q}(\mathcal{A})}_{C\times 1} \tag{16}$$

where the "hat" notation denotes a diagonal matrix with elements of $\boldsymbol{\pi}^{va}$ defining the diagonal elements. The coefficient vectors $\boldsymbol{\pi}^{comp}$ and $\boldsymbol{\pi}^{emp}$ are similarly defined and used to recover the domestic PHEB in worker compensation and employment terms (the construction of these coefficient vectors is also presented in the appendix).

Although it is algebraically feasible to transform the import PHEB from output value to value added, employment, and worker compensation terms by replacing $\Delta^{q}(\mathcal{A})$ with $\Delta^{m}(\mathcal{A})$ in equation (16), we do not undertake these calculations. The result of doing so could be interpreted as domestic-equivalent values (i.e., the value added that would arise if imports were produced domestically). Nevertheless, there is reasonable concern that within any particular BEA commodity definition, the goods and services being imported are sufficiently different from those produced domestically that such an interpretation would be inappropriate.

Data

The PHEB for domestic output in equation (13) and the PHEB for imports in equation (14) are calculated from six arguments: domestic commodity output (q), commodity imports ($\boldsymbol{m}$), and four direct requirements matrices ($\boldsymbol{R}^{dx}$, $\boldsymbol{R}^{dk}$, $\boldsymbol{R}^{mx}$, $\boldsymbol{R}^{mk}$). Transforming these results from output value to value added, worker compensation, and employment equivalents require an additional three arguments ($\boldsymbol{\pi}^{v\alpha}$, $\boldsymbol{\pi}^{comp}$, $\boldsymbol{\pi}^{emp}$). Table 2 below summarizes the data sources used to calculate these arguments. We briefly discuss these sources, leaving detailed explanations of the data manipulation steps to the appendix.

Table 2
Hypothetical extraction data sources

	Source table names	Source data product
q	Make Table	Input-Output Accounts Supplemental Estimates
$\boldsymbol{m}$	Import Table	Input-Output Accounts Supplemental Estimates
$\boldsymbol{R}^{dx}$	Use, Import, and Make Tables	Input-Output Accounts Supplemental Estimates
$\boldsymbol{R}^{dk}$	Use, Import, and Make Tables Nonresidential Detail Estimates (Investment) PEQ Bridge	Input-Output Accounts Supplemental Estimate Table Detailed Data for Fixed Asset and Consumer Durable Goods NIPA Underlying Estimates
$\boldsymbol{R}^{mx}$	Import and Make Tables	Input-Output Accounts Supplemental Estimates
$\boldsymbol{R}^{mk}$	Use, Import, and Make Tables Nonresidential Detail Estimates (Investment) PEQ Bridge	Input-Output Accounts Supplemental Estimates Detailed Data for Fixed Asset and Consumer Durable Goods NIPA Underlying Estimates
$\boldsymbol{\pi}^{v\alpha}$	Use, Import, and Make Tables	Input-Output Accounts Supplemental Estimates
$\boldsymbol{\pi}^{comp}$	Use, Import, and Make Tables	Input-Output Accounts Supplemental Estimates
$\boldsymbol{\pi}^{emp}$	Use, Import, and Make Tables Employment by NAICS Industries, U.S. Total	Input-Output Accounts Supplemental Estimate Tables Quarterly Census of Employment and Wages (QCEW)

NIPA= National Income and Products Accounts.

Source: USDA, Economic Research Service.

The BEA Input-Output Accounts report the production of commodities by industry (Make Table) and the use of commodities (domestic and imported) by households, businesses, government, and foreign trade (Use Table). The use of commodities as intermediate inputs by businesses is reported by industry, while the purchase of commodities for use as capital by private businesses is only reported as national totals in three classes: equipment, structures, and intellectual property. The Import Table reports the same information as the Use Table for imported commodities. A domestic counterpart is then built by differencing the Import Table from the Use Table. BEA publishes several versions of the Input-Output Accounts, and for this analysis, we use the "before redefinitions" tables denominated in producer prices.

Because the Use Table does not report commodity investment by industry, we construct this information from several data sources. BEA publishes annual purchases of capital goods by industrial sector in its Fixed Asset and Consumer Durables product.[7] For structures and intellectual property, the crosswalk between the capital goods reported in the Fixed Asset tables and the BEA commodities in the Input-Output Accounts is based on matching names between data sources. For equipment, BEA publishes the PEQ Bridge as part of its National Income and Product Accounts (NIPA) that reports the composition of capital goods across BEA commodities. These data are combined to allocate the private investment of fixed assets reported in the Use Table to industries.

Industry value added and employee compensation are included in the Use Table. These are translated to output coefficients in commodity terms using standard methods that combine information from the Use and Make Tables.

Industry employment is not reported in the Input-Output Accounts and is unique in our analysis as the only measure of activity that is not dollar denominated.[8] Instead, we use annual data from the Quarterly Census of Employment and Wages (QCEW) for 2017, which provides national employment at the six-digit NAICS level.[9] The BEA provides a cross-walk between NAICS and BEA detail-level industries.[10]

There are some important caveats to the QCEW employment numbers. First, these numbers are collected from State unemployment insurance records and therefore do not cover all employees. In 2017, there were 143,859,900 jobs in QCEW and 151,949,000 wage and salary jobs in the BEA's estimate for the entire economy. QCEW coverage was therefore around 95 percent. Notably, agricultural workers are subject to several unemployment insurance coverage exemptions under the Federal Unemployment Tax Act (FUTA) that do not apply to non-agricultural workers. As a result, QCEW only captures 74 percent of salary and wage workers in agricultural industries.

[7] These transactions are recorded by capital ownership, not use. If a farmer purchases a tractor, that is a capital purchase by the agricultural sector and is captured directly in $\boldsymbol{R}^{dk}$. If a farmer leases a newly purchased tractor from an equipment leasing company, the capital contribution to the PHEB will be indirect. The lease is a direct intermediate input captured in $\boldsymbol{R}^{dx}$. The capital purchases of the leasing and rental sector are indirectly assigned to agriculture through the Leontief inverse (e.g., if 5 percent of leasing and rental output is an input to agriculture, then 5 percent of their capital portfolio will be assigned to agriculture).

[8] In other words, the Input-Output Accounts report the dollar value of labor inputs (employee compensation), not the quantity of labor, just as it reports the dollar value of grain output, not the quantity of grain produced.

[9] QCEW reports the number of jobs by sector. The number of jobs is different than the number of people employed. Multiple jobholders show up more than once. We also do not distinguish between full-time and part-time work; each counts as a single job.

[10] In general, every BEA detail-level industry is an aggregate of one or more NAICS six-digit industries. Thus, BEA industry employment is the sum of employment in the associated NAICS industries. The most important exception to this rule is all activity in the Construction sector: NAICS industry codes are based on shared production technology (e.g., electricians, plumbing, carpentry, etc.), while BEA organizes construction by the building usage (residential housing, office and commercial, health care, educational, etc.). Thus, construction can only be mapped between NAICS and BEA taxonomies by aggregating to the 2-digit level.

Second, proprietors and general partners are generally not considered employees of the business they operate. Thus, the QCEW figures do not include their labor in employment totals. Treating these self-employed positions as jobs, there were 196,394,100 jobs according to the BEA, and thus QCEW only attains 73-percent coverage. The fraction of jobs that are proprietorships varies across industry: proprietors account for 69 percent of farm jobs, but just 22 percent of non-farm jobs. QCEW also does not include unpaid family workers, an important source of labor for farms. Because the variation across industries makes it impossible to simply "scale up" the numbers we estimate for unemployment insurance eligible jobs, we treat our estimates for employment as a lower bound.

Results

Output Upstream of Agricultural Production

Table 3 shows the contribution of agricultural producers to the U.S. economy through their demand for agricultural and non-agricultural commodity inputs. The total PHEB of agricultural production is $570.1 billion in total supply. Of this, most (90 percent) is attributable to domestically produced output. Around 82 percent of that output is from non-agricultural commodities, including chemicals, machinery, and services. Imports are $55.0 billion, and an even larger fraction of these are non-agricultural (95 percent).

Table 3
Value of supply and use upstream of domestic agricultural producers in 2017 (U.S. dollars, million)

	Output	Imports	Supply	Domestic intermediate inputs	Domestic capital	Imported intermediate inputs	Imported capital	Use
Non-agricultural	424,908	52,073	476,981	347,435	77,473	35,729	16,345	476,981
Agricultural	90,216	2,952	93,168	90,216	0	2,952	0	93,168
Total	515,124	55,025	570,149	437,651	77,473	38,681	16,345	570,149

Note: Numbers may not add up due to rounding.

Source: USDA, Economic Research Service.

The hypothetical extraction results show the important role of agricultural commodities as intermediate inputs to other agricultural producers. We again emphasize this is not predicting what would happen if the agricultural sector disappeared. There is no change in the final demand for agricultural goods, nor are we assuming producers are hit with a negative productivity shock. The $90.2 billion of output value reported in table 3 for domestic agricultural producers arises entirely because of their provision of inputs, directly or indirectly, to other agricultural producers.

Value Added, Worker Compensation, and Employment

As previously noted, output value is an incomplete measure of real economic activity, as it ignores the associated costs of producing goods and services or the benefits that flow to employees. Therefore, table 4 reports the total contribution of agricultural production to value added, employee compensation, and employment through the demand for inputs. In producer prices, value added is $241.1 billion. For comparison, the level of value added by farms was $156 billion. For additional context, U.S. GDP in 2017 was $19.612 trillion, so the value added from domestic activity upstream of agricultural producers represents 1.23 percent of the entire economy and is greater than the total farm economy (0.80 percent). Non-agricultural commodities account for a slightly larger share of value added than they do in total output, about 88 percent.

Table 4

Value added, employee compensation, and employment upstream of agricultural producers in 2017

	Value added (U.S. dollars, millions)	Compensation (U.S. dollars, millions)	Employment (jobs)
Non-agricultural	212,936	113,116	1,466,386
Agricultural	28,194	5,647	96,269
Total	241,130	118,763	1,562,655

Source: USDA, Economic Research Service.

The value of employee compensation associated with activity upstream of agricultural production in the agricultural supply chain is $118.8 billion, which is almost three times the $40 billion in employee compensation in the farm sector itself. The value of employee compensation upstream of agricultural production is 1.14 percent of the $10.4 trillion of total compensation in the U.S. economy. Thus, the compensation share of upstream activity (1.14 percent) is smaller than the value added share (1.23 percent).

Approximately 1.56 million jobs, or 1.28 percent of all private sector jobs in the United States, are attributable to activity upstream of agricultural producers. About 6.2 percent of employment upstream of agricultural production is associated with the production of other agricultural commodities. Recall, agricultural employment in the QCEW does not include proprietors and general partners. Given the large number of self-employed operators in agricultural production industries, these employment figures are potentially a significant underestimate of the number of individuals whose economic well-being is tied to the supply of inputs to agricultural production. In the 2017 QCEW, 0.88 percent of jobs are in the NAICS industries 111–114, which includes agriculture, forestry, fishing, and hunting (but not support services). BEA reports 1.9 percent, 2.16 times as many. If we multiply the number of jobs upstream of agricultural production in agricultural industries by 2.16 and assume all non-agricultural workers are accounted for in the QCEW, there are about 1.67 million jobs associated with the production of inputs for agricultural operations, of which nearly 208,000 would be agricultural (12.4 percent).

Direct and Indirect Contributions

Table 5 decomposes PHEB into direct and indirect components. Recall that the direct component captures the value of inputs purchased by agricultural producers themselves. The indirect components capture second-, third-, and higher-order linkages in the supply chain upstream of agricultural producers (e.g., the chemicals purchased by pesticide manufacturers, the energy purchased by chemical manufacturers, etc.).

Table 5

Value added, employee compensation, and employment upstream of agricultural producers in 2017

	Output (U.S. dollars, millions)		Value added (U.S. dollars, millions)		Compensation (U.S. dollars, millions)		Employment (jobs)	
	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect
Non-agricultural	213,456	211,452	105,541	107,395	55,681	57,435	802,243	664,143
Agricultural	80,445	9,771	25,399	2,795	5,016	631	86,878	9,391
Total	293,901	221,223	130,940	110,190	60,697	58,066	889,121	673,534

Source: USDA, Economic Research Service.

This decomposition shows the importance of considering industries that are not direct suppliers to farms. Of the $515.1 billion in output value attributable to upstream agricultural activity, $293.9 billion is from the direct supply of inputs to agricultural producers, while another $221.2 billion (42.9 percent) arise from indirect pathways. In fact, 41.0 percent of upstream agricultural activity is from non-agricultural commodities that are not directly supplied to agricultural producers. This segment of the agricultural supply chain is even more important if we look at value added or compensation: 88.3 percent of the value added comes from non-agricultural commodities and 44.5 percent comes from non-agricultural commodities that are indirect. Almost half (48.4 percent) of the compensation arising from upstream agricultural activity arises from the production of non-agricultural commodities that are not directly supplied to agricultural producers.

Commodity-level Contributions

Although the activity upstream of agricultural producers is widespread across economic sectors, it is also highly skewed toward specific activities among the more than 400 commodities in the BEA input-output tables. In table 6, we list the commodities that account for the largest contributions toward upstream activity, organizing these by the 5 largest contributors (measured by the value of output) within agriculture, the 10 largest non-agricultural commodities (excluding transportation and wholesaling), and the 3 largest within the transportation and wholesaling sector. Together, these 18 commodities account for 52 percent of the domestic output value of upstream inputs, 48 percent of the value added, 45 percent of the compensation, and 49 percent of the employment.

Some of the largest contributors are commodities very clearly associated with agriculture, including beef cattle ranching,[11] support activities for agriculture and forestry, pesticide manufacturing, fertilizer manufacturing, and farm machinery and equipment manufacturing. Many of these commodities only reach farmers through wholesaling intermediaries, however, and nondurable wholesaling accounts for the greatest contribution to upstream agricultural activity in terms of output value (7.7 percent) and value added (9.3 percent). Only support activities for agriculture and forestry contribute more to compensation and employment.

Also notable are the many commodities listed among the largest contributors that are also commonly used by non-agricultural businesses. Such commodities include real estate services, construction, petroleum refining, truck transportation, and insurance. This highlights the measurement error that will arise when attempting to define upstream or downstream solely by industry definition rather than an explicit empirical approach.

Also notable is the heterogeneity in contribution across economic measures. Beef cattle ranching provides a larger contribution than support activities when measured in output value, but support activities contribute nearly twice the value added (30 times the compensation, and 15 times the number of jobs). As another example, the value of output upstream of agricultural production is approximately the same for support activities and other animal food manufacturing, but support services contribute 5 times the value added, 7 times the compensation, and 13 times the number of jobs. These examples illustrate the importance of explicitly defining the economic dimension along which commodities are identified as important contributors to upstream agricultural activity.

[11] Beef cattle ranching and farming include both ranches (112111) and feedlots (112112), so some of the importance is "built in" by being a large industry that supplies many inputs to itself.

Table 6
Largest domestic contributors to upstream agricultural activity in 2017 by commodity

BEA commodity	Output (U.S. dollars, millions)	Value added (U.S. dollars, millions)	Compensation (U.S. dollars, millions)	Employment (jobs)
Agricultural industries (five largest by value of output)				
Beef cattle ranching and farming	35,940	11,144	502	21,219
Grain farming	21,028	3,563	1,144	18,194
Oilseed farming	10,874	5,028	302	1,429
Poultry and egg production	8,939	1,166	506	8,727
Animal production, except cattle and poultry and eggs	3,826	2,637	345	6,931
Non-agricultural industries, excluding trade and transportation (10 largest by value of output)				
Support activities for agriculture and forestry	25,608	19,278	14,698	329,812
Other animal food manufacturing	23,521	3,597	1,890	25,265
Other real estate	14,573	5,982	1,142	15,308
Farm machinery and equipment manufacturing	13,943	5,409	3,200	32,439
Other nonresidential structures	11,659	6,772	4,438	56,341
Pesticide and other agricultural chemical manufacturing	10,076	3,961	1,088	8,898
Petroleum refineries	8,859	1,968	310	1,525
Scientific research and development services	7,655	4,255	2,928	18,039
Management of companies and enterprises	7,129	4,640	4,069	28,562
Insurance carriers, except direct life	7,057	3,758	1,396	11,213
Trade and transportation (three largest by value of output)				
Other nondurable goods merchant wholesalers	39,848	22,401	10,164	104,460
Truck transportation	14,068	6,823	3,689	55,652
Other durable good merchant wholesalers	4,758	2,517	1,270	16,793

BEA = U.S. Department of Commerce, Bureau of Economic Analysis.

Source: USDA, Economic Research Service.

Imports

The results reported in table 3 indicated that about 10 percent of output value upstream of agricultural production came from imported goods and services. To compare imported with domestically produced production inputs, we present results that aggregate commodities into broad supersectors (table 7).[12] We also split up the sector corresponding to NAICS 11 into agricultural production and support services for agriculture.

[12] The categories in the last "other" supersector include industries in sector 81, government, and industries with codes beginning with "S" in the BEA tables. These "S" industries are Other State and local government enterprises, Noncomparable imports, and Rest of the world adjustment.

Table 7
Value of supply and use upstream of domestic agricultural producers in 2017 by supersector (U.S. dollars, millions)

Supersector (NAICS)	Domestic output	Imports	Supply = use
Agriculture, forestry, fishing, and hunting (111–114)	90,216	2,952	93,168
Support services for agriculture, forestry, fishing, and hunting (115)	25,608	123	25,731
Mining, utilities, construction (21–23)	47,971	3,133	51,103
Manufacturing (31–33)	134,867	43,288	178,155
Trade and transportation (42–49)	104,107	258	104,365
Information; finance and insurance; Real estate and rental and leasing; Professional and business services (51–56)	104,990	2,471	107,461
Educational services; Health care and social assistance (61–62)	155	0	156
Arts, entertainment, and recreation; Accommodation and food services (71–72)	3,907	3	3,910
Other services, government, and miscellaneous	3,303	2,797	6,100
Total	515,124	55,025	570,149

Note: Numbers may not add up due to rounding.

Source: USDA, Economic Research Service.

The sectors that contribute the largest value of domestic output to activity upstream of agricultural producers are the sectors containing manufacturing (31–33), finance, information, and real estate (51–56), and trade and transportation (42–49). Support services for agriculture is the 6 largest category, only above arts (71–72), educational services (61–62), and other services.

Sectors differ in their import composition. The sectors that produce physical production inputs, like manufacturing or mining, tend to have a larger fraction of total supply from imports. Even among these sectors, there is variation. Imports account for 24.2 percent of upstream supply from manufacturing activities, compared to 6.1 percent of the upstream value from mining, utilities, construction. In subsequent analyses, we compare the import composition of specific commodities.

Table 8 reports the value of top imports at the commodity level. Several commodities, like beef cattle ranching and farming, show up as the largest in both domestic output and imports, but the relative importance of imports varies significantly across commodities. For example, the value of imported beef cattle ranching that is upstream of agricultural producers is $453 million, which is 1.3 percent the value of domestically produced output. For commodities like "Fruit and tree nut farming" or "Storage battery manufacturing," though, imports are greater than domestic output. The fourth-largest contribution among imported commodities is "Noncomparable imports." These include imports that do not have a comparable domestic industry, as well as foreign travel by U.S. business travelers.

Table 8
Value of import supply upstream of domestic agricultural producers in 2017 by commodity (U.S. dollars, millions)

BEA commodity	Imported output	Domestic output
Agricultural industries (five largest by value of output)		
Grain farming	647	21,028
Beef cattle ranching and farming	453	35,940
Fruit and tree nut farming	413	379
Fishing, hunting, and trapping	322	28
Greenhouse, nursery, and floriculture production	286	2,508
Non-agricultural industries, excluding trade and transportation (10 largest by value of output)		
Petroleum refineries	3,362	8,859
Oil and gas extraction	2,772	3,413
Fertilizer manufacturing	2,718	6,175
Noncomparable imports	2,659	N/A
Farm machinery and equipment manufacturing	1,946	13,943
Other basic organic chemical manufacturing	1,732	3,852
Storage battery manufacturing	1,373	321
Pesticide and other agricultural chemical manufacturing	1,294	10,076
Iron and steel mills and ferroalloy manufacturing	979	2,777
Other motor vehicle parts manufacturing	886	896

BEA = U.S. Department of Commerce, Bureau of Economic Analysis.

Source: USDA, Economic Research Service.

Implications for Productivity Measurement

Identifying the largest contributors to the agricultural supply chain upstream of farms provides insight to potential drivers of total factor productivity growth. Unlike most sectors of the economy, aggregate output growth in agriculture has largely been the result of increased productivity (Jorgenson et al., 2014; Wang et al., 2024).

First, public and private investment in research and development has resulted in technological improvements embedded in intermediate factor inputs, such as seeds, chemicals, breeding and genetics, machinery, and electronics (Fuglie et al., 2019). These gains have been reflected in a notable redistribution of input usage by U.S. agricultural production. For example, the share of intermediate inputs used in production has climbed steadily since the end of World War II, increasing 109 percent between 1948 and 2021, while the input shares of labor and land fell 76 and 28 percent, respectively (Wang et al., 2024).

Second, the increasing importance of support service providers who undertake many of the production and management activities typically associated with farm and ranch operations has also been noted (Dunn, 2024; Babkin et al., 2022) and we find that agricultural support services are the largest source of value added upstream of agricultural producers. These establishments may benefit from economies of scale and scope that allow greater capital intensity and more rapid adoption of new technologies. Thus, the reorganization of agricultural production across firm boundaries through vertical disintegration may be both an independent driver of productivity growth, as well as one that mediates the gains from technological improvements (Babkin et al., 2022).

The USDA, ERS U.S. agricultural productivity estimates incorporate hedonic price indices to quality adjust measures of fertilizer, pesticide, and contract labor inputs (USDA, ERS, 2024; Ball et al., 2016; Shumway et al., 2017). Our results suggest further work documenting quality improvements and price changes in intermediate inputs could be valuable additions.

Conclusion

Agricultural production in the United States relies on a wide array of inputs. Identifying the industries that contribute to the production of these inputs and quantifying the activity that is associated with the agricultural supply chain informs several areas. First, accounting for the economic activity that is attributable to the inputs used to produce agricultural commodities provides a more complete accounting of the total contribution of the agricultural supply chain to the U.S. economy. Second, a decrease in the price or increase in the quality of inputs can drive productivity gains, thus identifying the industries upstream of farms and ranches in the supply chain points to possible sources for domestic agricultural total factor productivity growth.

We find that economic activity by domestic businesses upstream of domestic agricultural producers accounts for more than $515 billion in total output, $241 billion in value added, $119 billion in payroll, and more than 1.56 million jobs. These results indicate that domestic agricultural producers contribute significantly to the U.S. economy through their demand for goods and services, and that failing to account for the economic activity associated with the agricultural supply chain upstream of farms understates the total contribution of agricultural production to the U.S. economy.

To further characterize upstream agricultural activity, we further decompose these totals across product type, position in the supply chain, and commodity. First, because some of the inputs used by agricultural producers are derived from other agricultural producers (e.g., animal feed used by livestock operations was made using grain and oilseed), we also allocate these totals into separate contributions for agricultural and non-agricultural commodities. Domestic production of non-agricultural commodities upstream of agricultural producers accounts for $425 billion in total output, $213 billion in value added, $113 billion in payroll, and 1.47 million jobs in non-government industries.

Second, because the agricultural supply chain connects businesses engaged in a wide range of activities through numerous production steps and supply linkages, we also calculated the contribution arising from the production of the inputs purchased directly by agricultural producers separate from the contributions arising farther back in the supply chain. Approximately 60 percent of the value of output attributable to the agricultural supply chain upstream of farms is derived from goods and services immediately adjacent to the farm gate. The seed, animal feed, fertilizer, pesticide, machinery, fuel, and various professional, business, and technical services that agricultural producers purchase account for $294 billion in total output value and $131 billion in value added. But, each of these inputs is produced by a business with its own input needs, and each of those businesses also have input needs, on backward (e.g., the fertilizer manufacturer uses the output from chemical manufacturers and those chemical manufactures use the output from mining operations). These linkages in the agricultural supply chain that indirectly support domestic agricultural production account for a further $221 billion in output value and $110 billion in value added.

Finally, we find that the largest non-agricultural contributors to upstream agricultural activity are support services for agriculture and forestry, animal food manufacturing, pesticide and agricultural chemical manufacturing, petroleum refining, and insurance carriers. Nevertheless, the range of sectors that contribute to domestic agricultural production through both the direct and indirect provision of inputs is broad, with professional, technical, and business services, as well as trade and transportation activities also accounting for significant value added, employment, and payroll. In some industries, like fertilizer or farm machinery, a substantial percentage of upstream activity is occurring overseas as U.S. producers import needed inputs. While some of these inputs are general in nature (e.g., petroleum products, insurance), many are strongly associated with agricultural production (most fertilizer is used by agricultural operations) or have specific knowledge or training requirements when applied to agricultural operations (e.g., agricultural law and farm accounting). Identifying commodity-level upstream agricultural activity provides potentially useful guidance on identifying sources of total factor productivity growth in agricultural production. These results could also be used in future work to more completely describe the spatial distribution of economic activity associated with the agricultural supply chain, particularly its contribution to urban and rural economies (Davis et al., 2022).

This report fills a gap in the existing portfolio of USDA, ERS products that report on the agricultural supply chain by focusing specifically on the contribution to the U.S. economy of businesses upstream of agricultural producers. However, there are several limitations that warrant mention.

First, the preceding analysis applies a single technology to national-level data. Extending the analysis to the region or State level, perhaps allowing technology to vary across geographic areas, could provide additional information to researchers and policymakers.

Second, the approximately 400 industries and commodities included in the BEA detail-level I/O tables still involve a substantial degree of aggregation. For example, wheat, corn, and rice farming are aggregated to the commodity/industry Grain farming. Similarly, cattle ranches and feedlot operations are combined in the commodity/industry Beef cattle ranching and farming. Further disaggregation of agricultural products may increase the accuracy of estimates. Because these crops tend to concentrate in particular areas of the country, further disaggregating agricultural industries may be particularly valuable when extending the analysis to regions or States.

Third, these results present a snapshot of the economy from 2017. Providing an annual data series that covers more recent years would require a significant increase in methodological complexity because of existing data limitations. Specifically, BEA publishes detail-level data every 5 years, coinciding with the Economic Census and the Census of Agriculture. The construction of the supply and use tables is a significant undertaking and thus data are made available with a substantial lag—the 2017 supply and use tables were published in 2023 and tables based on data from the 2022 censuses will not be available until 2028. Nevertheless, data at the summary level (which includes 71 industries) are published annually, with only a 1-year lag. These data are too aggregated to generate accurate estimates on their own but could be used to impute annual detail-level supply and use tables.

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Appendix

This appendix describes in detail the raw data, processing, and methods for producing the results reported in the Results section of the report.

Input-Output Tables

In this application, production and use of commodities is summarized in the Input-Output (I/O) tables (Make, Use, and Import) at the detail level under the Make-Use framework in producer prices before redefinitions.

There are commodities and industries defined in the U.S. Department of Commerce, Bureau of Economic Analysis (BEA) taxonomy that capture important features of contemporary economic systems, but which account for an exceptionally small percentage of total activity and whose inclusion in particular applications can generate illogical findings. In our case, two such problematic commodities are Scrap (S00401) and Used and second-hand goods (S00402), neither of which have associated industries.

About a quarter of all scrap is generated as secondary products and appears in the Make Table (e.g., millwork and plywood manufacturing yield off-cuts that are sold to wood chip manufacturers). The remaining domestic supply of scrap and the entire domestic supply of used goods, however, is allocated through the Use Table because these items were produced in previous periods. For example, selling a machine that is being replaced by a newer model or scrapping it for the value of its metal components, is treated as offsetting negative entries for private fixed investment in equipment. We have found that this accounting rule can result in negative values on the estimated backward linkages for some scrap or used-good intensive industries in the hypothetical extraction method. To avoid this nonsensical result, we remove the commodities Scrap and Used and second-hand goods from the columns of the Make Table and recalculate total industry output over the remaining commodities, effectively shifting $10.7 million in national output (0.03 percent of total output value) to fixed demand. We also remove Scrap and Used and second-hand goods from the rows of the Use and Import Tables, reducing national intermediate expenditures by $58.0 million (0.4 percent of total intermediate use). Nevertheless, to properly account for the contribution of activity upstream of agricultural production, we do not recalculate industry value added.

Derivation of the Requirements Matrices

The BEA Input-Output tables are organized under an industry-commodity framework. Because the industry-commodity correspondence is not one to one (there are industries without corresponding commodities and commodities without corresponding industries), an industry-by-commodity requirements matrix is not generally invertible, a necessary property for the hypothetical extraction approach. Therefore, to construct an invertible requirements matrix, we operationalize the hypothetical extraction in commodity terms under an industry technology assumption.

Recall that the domestic supply-use relationship is expressed as:

$$\underbrace{\boldsymbol{q}}_{C\times 1} = \underbrace{\boldsymbol{x}^d}_{C\times 1} + \underbrace{\boldsymbol{k}^d}_{C\times 1} + \underbrace{\boldsymbol{f}^d}_{C\times 1} \qquad (A1)$$

where domestic commodity output is allocated to either intermediate inputs used by domestic producers, private capital used by domestic producers, or final demand. Final demand includes household consumption and residential investment, government consumption and investment, exports, and changes in inventory. Define the domestic intermediate input direct requirements matrix as $\boldsymbol{R}^{dx}$ with element r^{dx}_{cicj} that equal the amount of commodity c_i that is needed as an intermediate input to produce one unit of commodity c_j. Analogously, define the domestic capital input direct requirements matrix as $\boldsymbol{R}^{dk}$. Then, we can re-express (A1) as:

$$\underbrace{\boldsymbol{q}}_{C\times 1} = (\underbrace{\boldsymbol{R}^{dx}}_{C\times C} + \underbrace{\boldsymbol{R}^{dk}}_{C\times C})\boldsymbol{q} + \underbrace{\boldsymbol{f}^{d}}_{C\times 1} = \underbrace{\boldsymbol{A}^{d}}_{C\times C}\boldsymbol{q} + \boldsymbol{f}^{d} \qquad (A2)$$

The supply-use equation for imported commodities is similarly defined:

$$\underbrace{\boldsymbol{m}}_{C\times 1} = \underbrace{\boldsymbol{x}^{m}}_{C\times 1} + \underbrace{\boldsymbol{k}^{m}}_{C\times 1} + \underbrace{\boldsymbol{f}^{m}}_{C\times 1} \qquad (A3)$$

where $\boldsymbol{m}$ is the vector of commodity imports, which is allocated to intermediate inputs used by domestic producers ($\boldsymbol{x}^{m}$), private capital used by domestic producers ($\boldsymbol{k}^{m}$), or final demand ($\boldsymbol{f}^{m}$). Letting $\boldsymbol{R}^{mx}$ and $\boldsymbol{R}^{mk}$ denote the imported direct input requirement and imported direct capital requirements matrices and substituting yields:

$$\boldsymbol{m} = \underbrace{\boldsymbol{R}^{mx}}_{C\times C}\boldsymbol{q} + \underbrace{\boldsymbol{R}^{mk}}_{C\times C}\boldsymbol{q} + \boldsymbol{f}^{m} = \underbrace{\boldsymbol{A}^{m}}_{C\times C}\boldsymbol{q} + \boldsymbol{f}^{m} \qquad (A4)$$

Domestic Intermediate Input Requirements (R^{dx})

The domestic intermediate input direct requirements matrix, $\boldsymbol{R}^{dx}$, is constructed following the same approach as the BEA RIMS II product (BEA, 2013). Denote the use matrix as $\boldsymbol{U}$ and the import matrix as $\boldsymbol{M}$. Then, the domestic use matrix, $\boldsymbol{U}^{d}$, is their difference:

$$\underbrace{\boldsymbol{U}^{d}}_{C\times N} = \underbrace{\boldsymbol{U}}_{C\times N} - \underbrace{\boldsymbol{M}}_{C\times N} \qquad (A5)$$

where every element $\boldsymbol{u}^{d}_{cn}$ denotes the amount of commodity c that is produced domestically and used as an intermediate input by industry n. Except for a handful of commodities or industries, the elements of the use, import, and domestic use matrices are non-negative.[13] When differencing generates an unreasonable negative element in the domestic use matrix, we assume that the import value is correct[14] and impute a domestic use value such that the import share in that cell is the average import share for that commodity. To maintain the equality in (A1), an increase in the use of a commodity as an intermediate input by one industry must be offset elsewhere. In this application, we reduce private inventory (a component of final demand, $\boldsymbol{f}^{d}$) by an equivalent amount.

A use matrix is assumed to represent the relationship between industry output and commodity input demand. The elements of every column report the value of commodities used as intermediate inputs to produce the observed total value of industry output. The domestic use matrix can therefore

[13] The two situations that allow for negative entries in the use matrix include the government sale of inventory from commodity reserves and the sale of used goods by industries. The latter does not arise in our implementation, as the commodity Used and second-hand goods is removed from the Make, Use, and Import tables.

[14] In personal communications with BEA, the agency reported that imports are easier to track than domestic production and if there is any disagreement, those values are more likely to be the correct ones.

be transformed by dividing its elements by the value of domestic production in the corresponding industry to generate the domestic unit commodity input demand matrix:

$$\underbrace{\boldsymbol{B}^d}_{C\times N} = \underbrace{\boldsymbol{U}^d}_{C\times N} \underbrace{\hat{\boldsymbol{y}}^{-\mathbf{1}}}_{N\times N} \tag{A6}$$

where $\hat{y}$ is a diagonal matrix with diagonal elements equal to the value of domestic industry production (the row sums of the make matrix). The elements $\boldsymbol{B}^d$ are then interpreted as unit industry input coefficients, i.e., to produce \$1 of output in industry n requires b_{cn}^d dollars of commodity c produced domestically as an intermediate input.

Let $\boldsymbol{V}$ denote the make matrix that records the amount of commodity c produced by industry n. Scaling $\boldsymbol{V}$ by domestic commodity output (the column sums of the make matrix) yields the commodity mix matrix:

$$\underbrace{\boldsymbol{D}}_{N\times C} = \underbrace{\boldsymbol{V}}_{N\times C} \underbrace{\hat{\boldsymbol{q}}^{-\mathbf{1}}}_{C\times C} \tag{A7}$$

where $\hat{\boldsymbol{q}}$ is a diagonal matrix with diagonal elements equal to the value of domestic commodity production. The elements of the $\boldsymbol{D}$ matrix are interpreted as unit commodity output coefficients, i.e., for every dollar of commodity c that is produced in the economy, d_{nc} dollars are produced by industry n. The $\boldsymbol{D}$ matrix is often used to translate commodity levels to the industry output amounts that would be necessary to produce those levels. For example, given a $C \times 1$ commodity output vector $\boldsymbol{z}$, then $\boldsymbol{Dz}$ is the $N \times 1$ vector of industry output that would result in the production of $\boldsymbol{z}$.

The domestic (commodity-by-commodity) intermediate input direct requirements matrix is then calculated as the product of $\boldsymbol{B}^d$ and $\boldsymbol{D}$:

$$\underbrace{\boldsymbol{R}^{dx}}_{C\times C} = \underbrace{\boldsymbol{B}^d}_{C\times N} \underbrace{\boldsymbol{D}}_{N\times C} \tag{A8}$$

Import Intermediate Input Requirements (R^{mx})

The derivation of the import (commodity-by-commodity) intermediate input direct requirements matrix follows similarly. The import matrix is transformed by dividing its elements by the value of domestic production in the corresponding industry to generate the import unit commodity input demand matrix:

$$\underbrace{\boldsymbol{B}^m}_{C\times N} = \underbrace{\boldsymbol{M}}_{C\times N} \underbrace{\hat{\boldsymbol{y}}^{-\mathbf{1}}}_{N\times N} \tag{A9}$$

The elements of $\boldsymbol{B}^m$ are then interpreted as unit industry input coefficients (i.e., to produce \$1 of output in industry n requires imports of b_{cn}^m dollars of commodity c as an intermediate input). The import (commodity-by-commodity) intermediate input direct requirements matrix is then calculated as the product of $\boldsymbol{B}^m$ and $\boldsymbol{D}$:

$$\underbrace{\boldsymbol{R}^{mx}}_{C\times C} = \underbrace{\boldsymbol{B}^m}_{C\times N} \underbrace{\boldsymbol{D}}_{N\times C} \tag{A10}$$

Capital Input Requirements

The Use Table reports private fixed investment of commodities over three classes: equipment ($\boldsymbol{k}^{eq}$), intellectual property ($\boldsymbol{k}^{ip}$), and structures ($\boldsymbol{k}^{st}$). The Import Table reports analogous information over imported commodities, $\{\boldsymbol{k}^{eq,m}, \boldsymbol{k}^{ip,m}, \boldsymbol{k}^{st,m}\}$, so that differencing yields investment over domestically produced commodities, $\{\boldsymbol{k}^{eq,d}, \boldsymbol{k}^{ip,d}, \boldsymbol{k}^{st,d}\}$. Unlike intermediate inputs, commodity sales for each class are only reported in the aggregate, rather than allocated to each industry. Because BEA does not currently publish a capital use matrix, we construct an analogue to the intermediate use matrix drawing on several data sources.

To maintain the adding-up conditions embedded in the I/O tables, for each of the three investment asset classes, our approach seeks to build commodity-industry weights, w_{cn}^{i} , such that:

$$k_{cn}^{i} = w_{cn}^{i} k_{c}^{i} \qquad (A11)$$

where k_{cn}^{i} is the purchase of commodity c by industry n for use as capital class i and k_{c}^{i} is the total private fixed investment of commodity c as capital class i. Because these weights sum to unity:

$$\sum_{n} k_{cn}^{i} = \sum_{n} w_{cn}^{i} k_{c}^{i} = k_{c}^{i} \sum_{n} w_{cn}^{i} = k_{c}^{i} \qquad (A12)$$

The calculation of these weights proceeds in distinct steps, each requiring a different set of data. A limitation of these data is that capital investment by industry is not further disaggregated into domestic and imported expenditures. Thus, we are only able to construct commodity-industry weights based on total purchases that are then applied to the domestic and imported capital investment vectors.

Investment in Fixed Assets by Industry

We begin with the industry capital investment information from the BEA Fixed-Asset Nonresidential Detailed Estimates. These data report purchases of 96 equipment, intellectual property, and structure asset types by 74 industrial sectors. Thus, the asset definitions in these tables differ from the detail-level BEA commodity taxonomy and the sector definitions differ from the detail-level BEA industry taxonomy.

BEA provides a crosswalk between the industrial sectors reported in the Fixed-Asset tables and NAICS industries, as well as a crosswalk between NAICS industries and BEA detail-level industries. We combine these to create a crosswalk from the Fixed-Asset industrial sectors to BEA detail-level industries, which results in every possible correspondence type: one-to-one, many-to-one, one-to-many, and many-to-many.

Let v_{as} denote the reported investment of asset a by industrial sector s in the Fixed-Asset data and v_{an} denote the (derived) investment of asset a by detail-level industry n. Finally, let g_{n} denote the gross operating surplus of detail-level industry n from the Use Table. Table A.1 summarizes the calculation of industry investment in assets for each correspondence type. One-to-one correspondences assign the investment of the industrial sector to the detail-level industry. When multiple industrial sectors map to a single detail-level industry (many-to-one), the sum of asset investment over those sectors is assigned. When an industrial sector is defined over multiple detail-level industries (one-to-many), asset investment is allocated across those industries in proportion to the industry share of gross operating surplus (i.e., capital's share of income).

Table A.1
Allocating fixed-asset purchases from sectors to detail-level industries

Fixed asset industrial sector (s) to detail-level industry (n) correspondence		Detail-level industry investment in asset (a)
One-to-one:	$n \to s$	$v_{an} = v_{as}$
Many-to-one:	$n \to \mathcal{S}_n = \{s_i, \ldots\}$	$v_{an} = \sum_{s_i \in \mathcal{S}_n} v_{as_i}$
One-to-many:	$s \to \mathcal{N}_s = \{n_i, \ldots\}$	$v_{an} = v_{as} \frac{g_n}{\sum_{n_i \in \mathcal{N}_s} g_i}$
Many-to-many:	$s_{DG} \to \{\mathcal{N}_{s_{DG}}, n^*_{DG}\}$	$n \in \mathcal{N}_{s_{DG}}\colon\ v_{an} = v_{as^{DG}} \frac{g_n}{\sum_{n_i \in \mathcal{N}_{s_{DG}}} g_i + .5 g_{n^*}}$
	$s_{NG} \to \{\mathcal{N}_{s_{NG}}, n^*_{NG}\}$	$n \in \mathcal{N}_{s_{NG}}\colon\ v_{an} = v_{as_{NG}} \frac{g_n}{\sum_{n_i \in \mathcal{N}_{s_{NG}}} g_i + .5 g_{n^*}}$
	n^*	$v_{an^*} = v_{as^1} + v_{as^2} - \sum_{n_i \in \{\mathcal{N}_{s_{DG}}, \mathcal{N}_{s_{NG}}\}} v_{an_i}$

Source: USDA, Economic Research Service.

There is one many-to-many correspondence in the Fixed Asset to detail-level industry correspondence that is relatively clean. The detail-level industry *Wholesale electronic markets and agents and brokers* (denoted n^*) maps to both the *Wholesale trade of durable goods* (s_{DG}) and *Wholesale trade of nondurable goods* (s_{NG}) industrial sectors in the Fixed Asset tables. We assign half the activity in this industry to each sector, denoted n^*_{DG} and n^*_{NG} respectively. Letting $\mathcal{N}_{S_{DG}}$ and $\mathcal{N}_{S_{NG}}$ denote the industries mapped entirely to s_{DG} or s_{NG}, respectively, we operationalize the allocation of asset investment to detail-level industries by breaking the many-to-many correspondence into a collection of one-to-many correspondences and applying the rules presented in table A.1.

Investment in Commodities by Industry

Calculating commodity-industry weights w^i_{cn} from v_{an} is a two-step process. First, investment in assets (v_{an}) is translated into investment in commodities (v_{cn}). Second, commodity-industry weights are then calculated as investment shares. For each of the three investment commodity categories (structures, intellectual property, and equipment), translating asset investment to commodity investment is slightly different but uses manually constructed crosswalk tables.

Structures

There are 32 investment structure asset types in the Fixed Assets data and 11 detail-level construction commodities in the I/O tables. To map asset types to commodities, we reasonably match based on asset and commodity titles while minimizing discrepancies in total investment between sources. The resulting relations are either one-to-one (e.g., *Educational and vocational structures*); many-to-one (e.g., *Hospitals, Special care, and Medical buildings* map to *Health care structures*); or many-to-many (e.g., total asset investment in *Petroleum and natural gas* and *Mining* matches total commodity investment in *Drilling oil and gas wells* and *Other support activities for mining*). The complete concordance is shown in table A.2.

The calculation of investment of commodity c in structures by industry n, v_{cn}^{st}, from v_{an} depends on concordance type, following the same rules defined in table A.1, assuming equal weighting (rather than gross surplus weighting) in one-to-many correspondences. In one-to-one relations, commodity investment by an industry equals the corresponding asset investment by the industry. In many-to-one relations, investments in several assets by a single industry are added up to a corresponding commodity. In the many-to-many case, assets within a group are again added up and we impose an assumption that industry distribution of investment is the same for each commodity within this group.

Table A.2

Asset-commodity concordance for structures

Fixed asset	BEA commodity
Hospitals (SB31) Special care (SB32) Medical buildings (SOO2)	Health care structures (233210)
Educational and vocational (SB20)	Educational and vocational structures (233262)
Manufacturing (SI00)	Manufacturing structures (233230)
Office (SOO1) Multimerchandise shopping (SC03) Food and beverage establishments (SC04) Warehouses (SC01) Mobile structures (SOMO) Other commercial (SC02)	Office and commercial structures (2332A0)
Petroleum and natural gas (SM01)	Drilling oil and gas wells (213111)
Mining (SM02)	Other support activities for mining (21311A)
Electric (SU30) Wind and solar (SU60) Gas (SU40) Petroleum pipelines (SU50) Communication (SU20)	Power and communication structures (233240)
Lodging (SB41)	Other real estate (531ORE)
Air transportation (SB43) Other transportation (SB45) Other railroad (SU11) Track replacement (SU12) Local transit structures (SB44) Other land transportation (SB46) Highway and conservation and development (SO04)	Transportation structures and highways and streets (2332C0)
Religious (SB10) Amusement and recreation (SB42) Farm (SN00) Water supply (SO01) Sewage and waste disposal (SO02) Public safety (SO03)	Other nonresidential structures (2332D0) All other wood product manufacturing (3219A0)

BEA = U.S. Department of Commerce, Bureau of Economic Analysis.

Source: USDA, Economic Research Service.

Because of differences in reporting across BEA products, there will be differences in aggregate commodity investment and private fixed investment in structures as reported in the Use Table: $\sum_n v_{cn}^{st} \neq k_c^{st}$. Therefore, we calculate industry investment shares and treat these as the commodity-industry weights in equation (A12):

$$w_{cn}^{st} = \frac{v_{cn}^{st}}{\sum_n v_{cn}^{st}} \qquad (A13)$$

Collecting the commodity-industry weights for investment in structures into the matrix W^{st}, the matrix of industry investment in structures through the purchase of domestically produced commodities is:

$$\underbrace{\boldsymbol{K}^{st,d}}_{C\times N} = \underbrace{\widehat{\boldsymbol{k}}^{st,d}}_{C\times C} \underbrace{\boldsymbol{W}^{st}}_{C\times N} \qquad (A14)$$

while for imported commodities it is:

$$\underbrace{\boldsymbol{K}^{st,m}}_{C\times N} = \underbrace{\widehat{\boldsymbol{k}}^{st,m}}_{C\times C} \underbrace{\boldsymbol{W}^{st}}_{C\times N} \qquad (A15)$$

Intellectual Property

The calculation of industry investment of commodities for use as intellectual property capital follows an identical process. First, we build a map from 25 intellectual property assets to 15 detail-level commodities (concordance in table A.3), apply the allocation rules from table A.1 (with equal weighting) to calculate v_{cn}^{ip}, and then calculate commodity-industry weights.

$$w_{cn}^{ip} = \frac{v_{cn}^{ip}}{\sum_n v_{cn}^{ip}} \qquad (A16)$$

Industry investment in intellectual property through the purchase of domestically produced and imported commodities is then:

$$\underbrace{\boldsymbol{K}^{ip,d}}_{C\times N} = \underbrace{\widehat{\boldsymbol{k}}^{ip,d}}_{C\times C} \underbrace{\boldsymbol{W}^{ip}}_{C\times N} \qquad (A17)$$

$$\underbrace{\boldsymbol{K}^{ip,m}}_{C\times N} = \underbrace{\widehat{\boldsymbol{k}}^{ip,m}}_{C\times C} \underbrace{\boldsymbol{W}^{ip}}_{C\times N} \qquad (A18)$$

Table A.3
Asset-commodity concordance for intellectual property

Asset	Commodity
Custom software (ENS2) Own account software (ENS3)	Custom computer programming services (541511)
Prepackaged software (ENS1)	Software publishers (511200) Data processing, hosting, and related services (518200) Noncomparable imports (S00300)
Pharmaceutical and medicine manufacturing (RD11) Chemical manufacturing, ex. pharma and med (RD12) Semiconductor and other component manufacturing (RD23) Computers and peripheral equipment manufacturing (RD21) Communications equipment manufacturing (RD22) Navigational and other instruments manufacturing (RD24) Other computer and electronic manufacturing, n.e.c. (RD25) Motor vehicles and parts manufacturing (RD31) Aerospace products and parts manufacturing (RD32) Other manufacturing (RDOM) Software publishers (RD40) Financial and real estate services (RD50) Computer systems design and related services (RD60) Scientific research and development services (RD70) All other nonmanufacturing, n.e.c. (RD80) Private universities and colleges (RD91) Other nonprofit institutions (RD92)	Scientific research and development services (541700)
Books (AE30)	Periodical publishers (511120) Book publishers (511130)
Theatrical movies (AE10) Long-lived television programs (AE20) Music (AE40) Other entertainment originals (AE50)	Directory, mailing list, and other publishers (5111A0) Motion picture and video industries (512100) Sound recording industries (512200) Radio and television broadcasting (515100) Cable and other subscription programming (515200) Photographic services (541920) Performing arts companies (711100) Independent artists, writers, and performers (711500)

n.e.c. = not elsewhere classified.

Source: USDA, Economic Research Service.

Equipment

For capital equipment, the construction of a crosswalk and investment allocation rules occurs in two steps. First, we match the 39 equipment-asset types in the Fixed Asset investment tables to the 25 NIPA equipment categories in the PEQ Bridge table, published by BEA (concordance in table A4). This concordance allows us to allocate industry investment in assets, v_{an}^{eq} to NIPA equipment categories, yielding $\boldsymbol{W}_{NIPA}^{eq}$, a $25 \times N$ matrix of NIPA category-by-industry investment.

Table A.4
Asset-PEQ category concordance for equipment

Asset	PEQ category
Mainframes (EP1A) PCs (EP1B) DASDs (EP1C) Printers (EP1D) Terminals (EP1E) Tape drives (EP1F) Storage devices (EP1G) System integrators (EP1H)	Computers and peripheral equipment
Communications (EP20)	Communication equipment
Nonelectro medical instruments (EP34) Electro medical instruments (EP35)	Medical equipment and instruments
Nonmedical instruments (EP36)	Nonmedical instruments
Photocopy and related equipment (EP31)	Photocopy and related equipment
Office and accounting equipment (EP12)	Office and acc ounting equipment
Nuclear fuel (EI11) Other fabricated metals (EI12)	Fabricated metal products
Steam engines (EI21) Internal combustion engines (EI22)	Engines and turbines
Metalworking machinery (EI30)	Metalworking machinery
Special industrial machinery (EI40)	Special industry machinery, not elsewhere classified
General industrial equipment (EI50)	General industrial, including materials handling, equipment
Electric transmission and distribution (EI60)	Electrical transmission, distribution, and industrial apparatus
Light trucks (including utility vehicles) (ET11)	Light trucks (including utility vehicles)
Other trucks, buses, and truck trailers (ET12)	Other trucks, buses, and truck trailers
Autos (ET20)	Autos
Aircraft (ET30)	Aircraft
Ships and boats (ET40)	Ships and boats
Railroad equipment (ET50)	Railroad equipment
Household furniture (EO11) Other furniture (EO12)	Furniture and fixtures
Other agricultural machinery (EO30) Farm tractors (EO21)	Agricultural machinery
Other construction machinery (EO40) Construction tractors (EO22)	Construction machinery
Mining and oilfield machinery (EO50)	Mining and oilfield machinery
Service industry machinery (EO60)	Service industry machinery
Household appliances (EO71) Other electrical (EO72)	Electrical equipment, not elsewhere classified
Other (EO80)	Other

Source: USDA, Economic Research Service.

The 2017 PEQ Bridge reports the commodity composition in dollar terms for each of the 25 National Income and Product Accounts (NIPA) equipment categories (i.e., a $C \times 25$ matrix). The set of products covered by a single commodity definition may be split amongst multiple NIPA equipment categories, and a single NIPA equipment category may include products that fall under multiple commodity definitions. Therefore, we scale each column of the PEQ Bridge matrix by total NIPA category investment to build a $C \times 25$ weight matrix, $\boldsymbol{W}_{PEQ}^{eq}$. Premultiplying $\boldsymbol{W}_{NIPA}^{eq}$ by $\boldsymbol{W}_{PEQ}^{eq}$ yields a matrix of commodity investment by industry with elements v_{ac}^{eq} that are used to create equipment commodity-industry weights:

$$w_{cn}^{eq} = \frac{v_{cn}^{eq}}{\sum_n v_{cn}^{eq}} \tag{A19}$$

with:

$$\underbrace{\boldsymbol{K}^{eq,d}}_{C\times N} = \underbrace{\widehat{\boldsymbol{k}}^{eq,d}}_{C\times C} \underbrace{\boldsymbol{W}^{eq}}_{C\times N} \tag{A20}$$

$$\underbrace{\boldsymbol{K}^{eq,m}}_{C\times N} = \underbrace{\widehat{\boldsymbol{k}}^{eq,m}}_{C\times C} \underbrace{\boldsymbol{W}^{eq}}_{C\times N} \tag{A21}$$

Requirements Matrices

The set of domestic commodity-by-industry matrices defined in equations (A14), (A17), and (A20) over different capital classes can be combined to create a domestic capital requirements matrix using the same steps as for intermediate inputs:

$$\boldsymbol{R}^{dk} = \underbrace{\boldsymbol{K}^{d}}_{C\times N} \underbrace{\widehat{\boldsymbol{y}}^{-\boldsymbol{1}}}_{N\times N} \underbrace{\boldsymbol{D}}_{N\times C} = (\boldsymbol{K}^{d,st} + \boldsymbol{K}^{d,ip} + \boldsymbol{K}^{d,eq})\widehat{\boldsymbol{y}}^{-\boldsymbol{1}}\boldsymbol{D} \tag{A22}$$

Similarly for the imported capital requirements matrix from equations (A15), (A18), (A21):

$$\boldsymbol{R}^{mk} = \underbrace{\boldsymbol{K}^{m}}_{C\times N} \underbrace{\widehat{\boldsymbol{y}}^{-\boldsymbol{1}}}_{N\times N} \underbrace{\boldsymbol{D}}_{N\times C} = (\boldsymbol{K}^{m,st} + \boldsymbol{K}^{m,ip} + \boldsymbol{K}^{m,eq})\widehat{\boldsymbol{y}}^{-\boldsymbol{1}}\boldsymbol{D} \tag{A23}$$

Value Added, Compensation, and Employment Coefficients

To construct commodity coefficient vectors $\boldsymbol{\pi}^{va}$, $\boldsymbol{\pi}^{comp}$ and $\boldsymbol{\pi}^{emp}$, we translate industry level information into commodity terms through the $\boldsymbol{D}$ matrix. Let va_n denote the value added to the economy by industry n, which is reported in the Use Table. Define the vector $\tilde{\boldsymbol{\pi}}^{va}$, with elements $\tilde{\boldsymbol{\pi}}_n^{va} = va_n/y_n$ that equal the value added per unit of industry output. To translate these values from industry to commodity terms, we can then compute:

$$\underbrace{\boldsymbol{\pi}^{va}}_{C\times 1} = \underbrace{\boldsymbol{D}'}_{C\times N} \underbrace{\tilde{\boldsymbol{\pi}}^{va}}_{N\times 1} \tag{A24}$$

Recall that the elements of the ***D*** matrix are unit commodity output coefficients (i.e., for every dollar of commodity c that is produced in the economy, $\boldsymbol{d}_{nc}$ dollars are produced by industry n). Thus, the columns of ***D*** sum to 1 and can serve as industry weights, where industries are weighted by their share of commodity output. By premultiplying $\tilde{\boldsymbol{\pi}}^{va}$ by the transpose of ***D***, the value added coefficient $\boldsymbol{\pi}_c^{va}$ for commodity c can be understood as the sum of value added coefficients of all industries producing c, weighted by their shares in commodity's production.[15]

The same logic is used for compensation and employment. For compensation, define the vector $\tilde{\boldsymbol{\pi}}^{comp}$ with $\tilde{\pi}_n^{comp} = comp_n / y_n$, where $comp_n$ is the compensation of employees in industry n from the Use Table. For employment, define $\tilde{\boldsymbol{\pi}}^{emp}$ with elements $\tilde{\pi}_n^{emp} = emp_n / y_n$, where emp_n is the national QCEW employment in industry n. We then calculate $\boldsymbol{\pi}^{comp}$ and $\boldsymbol{\pi}^{emp}$ using equation (A24).

[15] One can show that this formulation is algebraically equivalent to:

$$\underbrace{\Delta^{va}(\mathcal{A})}_{C\times 1} = \underbrace{\widehat{\boldsymbol{\pi}}^{va}}_{C\times C}\ \underbrace{\Delta^{q}(\mathcal{A})}_{C\times 1} = \underbrace{\widehat{\Delta^{q}}(\mathcal{A})}_{C\times C}\ \underbrace{\boldsymbol{\pi}^{va}}_{C\times 1} = \widehat{\Delta^{q}}(\mathcal{A})\ \underbrace{\boldsymbol{D}'}_{C\times N}\ \underbrace{\tilde{\boldsymbol{\pi}}^{va}}_{N\times 1} = \left(\underbrace{\boldsymbol{i}'}_{1\times N}\ \underbrace{\widehat{\tilde{\boldsymbol{\pi}}}^{va}}_{N\times N}\ \underbrace{\boldsymbol{D}}_{N\times C}\ \widehat{\Delta^{q}}(\mathcal{A})\right)'$$

where the last expression (reading left to right) decomposes commodity contributions into industry-commodity contributions, which are then translated into value added terms and summed across commodities.