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ABSTRACT

Input-output (I-O) analysis represents the flows of goods and services within the market. Environmentally-extended I-O (EEIO) models include flows of both pollution and consumption of resources and energy. The present paper proposes a conceptual structure for EEIO accounts that builds on the work of Leontief (1970) and Hendrickson, Lave, and Matthews (2006), and then estimates empirical EEIO accounts for the U.S. economy in 1999 and 2011. The empirical accounts provide the first complete characterization of the air pollution damage flows throughout the U.S. economy. Pollution intensity fell from 7 percent of value-added in 1999 to 2 percent in 2011. The utility sector exhibits the highest ratio of pollution damage from value-added production to supply chain damage; this ratio was 22 in 1999 and 54 in 2011. About one-half of all damage comes from intermediate demand, one-third from household consumption, and about 7 percent each from fixed investment and government use of commodities. In both 1999 and 2011, damages would have been about 7 percent higher had all imports been made domestically. The damages from exported goods nearly doubled from 5 percent to almost 10 percent of total pollution damage.

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Introduction.

Input-output (I-O) analysis explores the inter-dependencies among the different sectors of an economic system. While traditional I-O modeling represents the flows of goods and services within the market, environmentally-extended I-O (EEIO) models include flows of both residuals (pollution) and consumption of resources and energy. Many EEIO models exist (see reviews in European Union Joint Regulatory Centre, 2006, and Ronald E. Miller and Peter D. Blair, 2006). While the earliest conceptual augmentation is credited to Wassily Leontief (1970), importantly, the most prominent empirical work in this area models physical accounts. That is, EEIO models are used to explore the flows of emissions of pollutants and use of (energy-bearing) resources (Lester B. Lave et al., 1995; Christopher T. Hendrickson et al., 1998; Henderson, Lave, and H. Scott Matthews, 2006). Only two early examples of value-based EEIO modeling, using data now 23 years old, exist (Matthews and Lave, 2001; Matthews, 2000).

The present paper strives to contribute to this field by estimating the first economy-wide EEIO model for the United States (U.S.) economy reported in monetary terms using state-of-the-art economic and environmental modeling techniques. Specifically, this analysis develops an EEIO model for air pollution over all sectors of the U.S. economy that reports (monetary) external costs for 1999 and 2011. This facilitates a complete characterization of the monetary damage flows from air pollution within the U.S. economy inclusive of both intermediate and final demand. Capitalizing on the information in the market I-O accounts reported by the U.S. Bureau of Economic

Analysis (USBEA), the damages associated with production from each sector that is targeted for exports, private fixed investment, changes in physical inventories and government consumption are also reported.

The move from physical accounts to value, or monetary, accounts is a significant step forward. In the National Income and Product Accounts (NIPAs), the weights affixed to output of various goods and services in the economy are their market prices. Intuitively, different prices are attributed to different goods. In properly constructed environmentally augmented accounts, the weights applied to pollution emissions are their marginal damages (see William D. Nordhaus, 2006 or Katherine G. Abraham and Christopher Mackie, 2006). Analogously to market goods, prices affixed to emissions should reflect their value. Prior research indicates that the monetary damage of emissions for local pollutants varies considerably according to the source location (Nicholas Z. Muller and Robert O. Mendelsohn, 2009; Neal Fann et al., 2009; Paul Y. Kerl et al., 2015). As such, emissions of different pollutants, or of the same pollutant discharged in different locations, are effectively different goods (or bads, as the case may be). This suggests using source-and-pollutant-specific marginal damages as "prices" or weights. Such an approach appropriately values various emissions in the aggregate EEIO accounts[1]. The variance in damages (across sources of the same pollutant) also suggests that physical accounts which implicitly attribute equal weight to all emissions may yield biased environmental accounts. The use of marginal damages for valuation

[1] This is an important distinction from the one or two examples of monetary EEIO papers in the literature which used national average "prices" because of the dearth of models available at the time that could estimate source-and-pollutant-specific marginal damages.

has the additional virtue that this strategy most closely reflects the approach used in developing the market accounts. And, if the goal is a synthesis of market and environmental accounting structures, this isomorphism in method is especially helpful.

Estimating monetary EEIO accounts is also preferred because it facilitates a more direct or complete augmentation of the market accounts. Simply put: monetary EEIO models are expressed in the same units as the market accounts. As such, their direct inclusion into a fully augmented system of accounts is feasible. The physical accounts must remain separate or distinct from the market accounts because they are expressed in terms of tons, cords, barrels, BTUs, or some other physical unit of measure.

There are, of course, costs associated with the use of monetary EEIO methods. Perhaps the most important is the introduction of uncertainty. This manifests most clearly in two areas: the impact of exposure to environmental pollutants on various human health states, and the monetary value attributed to the changes in the risk of such health impacts occurring. While the uncertainty introduced by pursuing value accounts is significant (see United States Environmental Protection Agency (USEPA), 2011 for a characterization of the effects of different modeling choices on the benefits of air pollution control) all is not lost. That is, the two sources of uncertainty noted above effect the level of damage estimates, not the relative damage of emissions across sectors, industries, or sources (Muller, 2011). This occurs because both the functions that relate exposure to impact and impact to money are applied multiplicatively and uniformly across emitting sources. As such, the "relative damage" uncertainty cancels out.

Armed with monetary EEIO estimates, the paper presents a complete accounting of air pollution value flows throughout the economy. To begin, damages are estimated from value-added production. Using steel manufacturing as an example, pollution from value-added production is that which escapes the smokestack at the site of production as the various inputs to production are combined to make output. This is the most intuitive form of pollution. The second category involves external costs associated with the production of inputs that are then used in a given sector's production processes. So, continuing with the steel manufacturing example, this approach tabulates the damages from coal mining, electric power generation, railroad transport, and all of the other factors of production used by steel manufacturers (aside from labor and fixed capital). Third, the analysis inverts the previous classification by computing the pollution damage due to all other sectors' use of output by a given sector. This tack, in the context of steel production, totals up the damage from every sectors' use of manufactured steel as inputs to their production processes. Fourth, the pollution damage due to consumption of output by households is calculated. Finally, pollution damages are estimated for net exports, private fixed investment, and changes to inventories. It is critical to note that the above categories of pollution damage are not mutually exclusive and are not aggregated.

While the approach discussed above computes levels of pollution damage, perhaps equally important is that this approach enables several new ways to model the pollution intensity of production and consumption. Calculating pollution intensity is paramount because it facilitates cross-sectional and inter-temporal comparisons of pollution damage. Prior authors reported a standard measure of damage intensity either expressed in terms of damage-per-unit value-added or gross output (Muller, Nordhaus, Mendelsohn, 2011; Muller, 2014a). The present analysis reports this and additional intensity constructs. Akin to Hendrickson, Lave, and Matthews, (2006) this analysis computes the ratio of damage produced by a sector coming from value-added production relative to cumulative emissions produced in the supply-chain. Next, this paper reports the ratio of the cumulative externality due to other industries' use of each sector's commodities as inputs to production to total damage, by sector. Damages from household consumption of each sector's output are also calculated. This value is expressed relative to value-added damage and damages due to other sectors' use of commodities as inputs. The analysis also compares the damage intensity of exports and avoided domestic damage from imports.

As stated above, the empirical analysis conducted herein differs from most, if not all, prior EEIO models (Leontief, 1970; 1985; Lave et al., 1995; Hendrickson et al., 1998; Hendrickson, Lave, Matthews, 2006). As such a brief description of the exercises conducted is presented here with a more detailed discussion in section III. The analysis relies on several publicly available databases published by the USBEA. First, the "Use" table, which reports a sectoral breakdown of commodity use and industry output in nominal terms, is employed to obtain an annual glimpse of the flows of goods and services within the market boundary. (In contrast, most earlier research in environmental I-O used the "Direct Input Requirements" tables, which depicts the value of inputs required to yield one unit of output: e.g. Hendrickson, Lave, Matthews, (2006). The analysis also wields the USBEA's "Imports" matrix and the "Make" tables. The particular manner in which each of these databases is utilized is discussed below and in more detail in section III.

For environmental pollution damage, the analysis uses AP2, an integrated assessment model (Muller, 2011; 2014a; 2014b; Stephen P. Holland et al., 2015; Paulina Jaramillo and Muller, 2016) which is an updated version of the APEEP model (Muller, Mendelsohn, 2007; 2009; Muller, Mendelsohn, Nordhaus, 2011; National Academies of Science, National Research Council, 2010; Jeremy J. Michalek et al., 2011). AP2 estimates marginal damages ($/ton) for five common and economically important air pollutants. The marginal damages are estimated by source and pollutant. These are then effectively treated as prices in that they are multiplied by U.S. Environmental Protection Agency emission data (USEPA, 2002; 2014) to estimate total pollution damage. Armed with such assessments of pollution damage, a rudimentary measure of pollution intensity is estimated for every sector in the U.S. economy in 1999 and 2011. This metric reports monetary pollution damage per unit gross output, by sector, by year. The next step in the analysis is to couple the pollution intensity metric with USBEA tables. First, the Hadamard product of the pollution damage matrix and the USBEA "Use" table yields a total pollution damage matrix. The resulting matrix characterizes a comprehensive assessment of the pollution damage flows among economic sectors. This pollution damage matrix yields damages from input use and value-added production.

The pollution damages matrix described above enables the sector level analysis of pollution damage from: exports, private fixed investment, and changes to inventories. The pollution damage due to consumption (of each sector's output) by households is also estimated using the pollution damage matrix. Next, the USBEA's "Imports" matrix is used to estimate the avoided pollution damage due to imports; the Hadamard product of the imports matrix and the pollution intensity matrix generates a measure of pollution damage, by sector, for imports *had they been produced domestically.* This matrix is used to attenuate the estimated pollution damage matrix because imports reduce domestic pollution. (If imports are not accounted for, pollution from commodity use and some portion of personal consumption is attributed to domestic output, incorrectly.)

The empirical analysis uses emissions and market production data from the years 1999 and 2011. This twelve year period witnessed some significant changes in both the macroeconomy and the regulatory environment that make it worthy of study. For example, the recession following the technology sector correction in 2000-2001 and the Great Recession of 2008-2009 likely had implications for pollution intensities and gross pollution output. In terms of public policy, there were a number of interventions that occurred between 1999 and 2011. Notably, Phase II of the Acid Rain Program (ARP) commenced in 2000. Important transportation fuel pollution content regulations were enacted between 2004 and 2010. Further, a series of replacements for the ARP were proposed beginning in 2005. These “threats” of new, more stringent controls for the power generation sector were credible enough to yield behavioral changes among the regulated plants. Finally, the beginnings of what could be called climate policy were enacted toward the end of the time period under study. Importantly, the secular dimension of the analysis facilitates an assessment of how the various measures or categories of pollution damages change, by sector, in relative and absolute terms.

a. **Preview of Results.**

The empirical results begin by reporting how conventional or rudimentary measures of pollution intensity change, by sector, from 1999 to 2011. To summarize, pollution intensity fell by a factor of three from 1999 to 2011. There is, however, significant heterogeneity among sector in this rate of change. Next, the empirics report the rates of change in both value-added and input use along with the damages from each. Within the market boundary value-added and input use increased for most sectors. Outside the market, damages from value-added production and input use decreased. Hence, pollution intensity declined. Notably, 15 of the 19 sectors tracked show damages falling more rapidly from input use than from value-added production.

The measures of pollution intensity indicate that the utility sector exhibited the largest ratio of value-added production relative to input use. This ratio was over 21 in 1999 and 54 in 2011. The sectors with the next largest ratios (waste management) displayed a value of about seven. The next reported measure of pollution intensity is the ratio of pollution damage from value-added production for a given sector to that associated with all other sectors' use of output produced by the particular sector. The largest ratio is attributed to health care; this measure of pollution intensity was 33 in 1999 and 49 in 2011. (Emissions from this sector come from heating of facilities using fossil fuels. Consumption by other sectors of health care outputs is relatively emission free.)

The analysis reports that, in 1999, about one-half (56 percent) of pollution damage is due to intermediate demand and one-quarter of pollution impacts is from household consumption. Production to meet government demand for inputs and production targeted to private fixed investment each contributed about six or seven percent of total pollution damage. Finally, the creation of exported goods and services was responsible for the remaining 5 percent of external cost.

In 2011, these shares remained relatively stable despite the fact that overall pollution intensity fell dramatically. Damages from intermediate demand contributed 50 percent while household consumption comprised 30 percent of total damage. External costs from production to satisfy government demand and private fixed investment remained the same (as a share of total damage), while export damages increased to ten percent of total impacts. In both 1999 and 2011, avoided external costs due to importing goods and services amounted to roughly seven percent of total damage.

The remainder of this paper is comprised of section I. which develops the theoretical, or conceptual, structure which links this analysis to the prior literature and aims to emphasize the novelty of the current work. Section II. explores the empirical model used to estimate pollution damage. Section III. focuses on results and section IV. concludes.

I. The Input-output system.

An economic system consists of (n) industries consuming (m) commodities. Final consumption occurs in a household sector (h) over (m) commodities. Define technical coefficients for commodity (i) and industry (j),$\left(a_{i,j}\right)$ characterizing the monetary value of commodity (i) consumed, or used, by industry (j) in generating output. The $\left(a_{i,j}\right)$ are assumed to be defined per unit time corresponding to a typical accounting period, such as a year. Also note the distinction from a direct requirement table in which the technical coefficients are normalized by actual use: thus yielding per unit coefficients.

In a static framework, arranging all of the $\left(a_{i,j}\right)$ into matrix form yields a characterization of the flows of value within the economic system. Such a matrix is defined as A_1:

$$A_1 = \begin{pmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{m,1} & \cdots & a_{m,n} \end{pmatrix}$$

The empirical application features two distinct data years. As such, A_1 may vary across time, as the flows within the economy change. In order to maintain parsimony in the following notation, the time dimension is subsumed. Next, additional elements are added to A_1 that make the correspondence with the NIPA I-O tables complete. Namely: $H = (h_1 \quad \cdots \quad h_m)'$ reflects household or final consumption of each commodity input;

value-added, by industry, is denoted$V = (v_1 \quad \cdots \quad v_n)$; the sum of intermediate input use, is denoted ($U = u_1, u_2, \ldots u_n$); total input, which is the sum of intermediate input and value added, is ($C = c_1, c_2, \ldots c_n$). Finally, total intermediate output ($O = o_1, o_2, \ldots o_m$) and final demand ($X = x_1, x_2, \ldots x_n$) are included to form (A_2). Note that the sum of V and X (theoretically) balance and equal Gross Domestic Product (GDP).

$$A_2 = \begin{pmatrix} a_{1,1} & \cdots & a_{1,n} & o_1 & h_1 & x_1 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ a_{m,1} & \cdots & a_{m,n} & o_m & h_m & x_m \\ u_1 & \cdots & u_n & & & \\ v_1 & \cdots & v_n & & & GDP \\ c_1 & \cdots & c_n & & & \end{pmatrix}$$

a. Pollution flows in the system.

There are two primary avenues through which pollution may enter the economic system: via the use of commodities by industry and households and through final (value-added) production by each industry. Note the potential for imports and exports. Pollution from abroad may enter the economic system. Conversely, domestic emissions may alight upon foreign shores. Neither is able to be modeled empirically[2]. As such, these issues are left to future research. The analysis begins by exploring pollution from the use of commodities by industry.

[2] In contrast, domestic emissions from production of goods subsequently exported are encompassed. And avoided damages from imports are also modeled.

i. Pollution from use of commodities, by each industry.

Through the course of producing commodities, pollution, as yet generally defined, is generated. The pollution technical coefficient for commodity (i), denoted (g_i), represents the monetary value of pollution consequences due to the observed production of one monetary unit of commodity (i). The (g_i) are assembled into a vector G over all commodities[3]:

$$G = (g_1 \quad \cdots \quad g_m)$$

The product of a technical coefficient $\left(a_{i,j}\right)$ and a pollution technical coefficient (g_i), yields an estimate of the gross pollution consequence of use of commodity (i) by industry (j), per unit time. The product of (G) and (A_1), denoted D_1 (which is a (1 x n) vector), shows the total pollution consequence resulting from the use of all commodities (1) through (m) by each industry (1) through (n).

$$D_1 = GA_1 = (\sum_{i=1}^{m} a_1 g_i \quad \cdots \quad \sum_{i=1}^{m} a_n g_i)$$

ii. Pollution from commodity use, across industries.

While the vector D_1 contains entries that show damage from total commodity use *by each industry*, in this section the analysis is inverted to examine the pollution consequences from commodity use across industries. This analysis requires a matrix of pollution technical coefficients. Let $O = (1\ x\ n) = (1 \quad \cdots \quad 1)$.

[3] The procedures used to estimate the empirical coefficients in *G* are described in the empirical methods section.

Then: $F_1 = G'O = \begin{pmatrix} g_1 & \cdots & g_1 \\ \vdots & \ddots & \vdots \\ g_m & \cdots & g_m \end{pmatrix}$

where $F_1 = (m\ x\ n)$, and (F_1) consists of (n) replicates of (G). Then, a matrix of pollution consequence due to intermediate demand is given by:

$$H_1 = A_1 \cdot F_1 = \begin{pmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{m,1} & \cdots & a_{m,n} \end{pmatrix} \cdot \begin{pmatrix} g_1 & \cdots & g_1 \\ \vdots & \ddots & \vdots \\ g_m & \cdots & g_m \end{pmatrix}$$

Where $A_1 \cdot F_1$ denotes the Hadamard Product, or element-by-element multiplication, of A_1 by F_1.

The vector D_2 assembles the row sums of H_1. This shows total pollution consequence, or impact, due to the use of each commodity across industries (1) through (n).

$$D_2 = \begin{pmatrix} \sum_{j=1}^{n} a_j g_1 \\ \vdots \\ \sum_{j=1}^{n} a_j g_m \end{pmatrix}$$

Contrasting D_1 to D_2, note that each entry in D_1 reports, effectively, pollution damage from each industry's consumption of *all* commodities. D_2 reports pollution damage from the use of each commodity across *all* industries.

iii. Household final demand.

While D_2 captures pollution consequences from total commodity use in production, this structure omits final consumption by households. Let $h_1 g_1$ = total pollution damage due to household consumption of commodity (1). The vector of total pollution consequence due to commodity consumption by industries and by households is shown in D_3:

$$D_3 = \begin{pmatrix} \sum_{j=1}^{n}(a_j g_1) + h_1 g_1 \\ \vdots \\ \sum_{j=1}^{n}(a_j g_m) + h_m g_m \end{pmatrix}$$

iv. Value-added and "end-of-pipe" pollution.

Corresponding to final (value-added) production, for each industry (1,…,n), is a pollution technical coefficient measuring monetary pollution impact, per unit value-added. These coefficients, assembled in a vector and designated $E = e_1 \cdots e_n$, are intended to capture the pollution intensity of the production activities of each industry, net of pollution impacts from firms' use of commodities. Hence, the $E = e_1 \cdots e_n$ embody "end-of-pipe" pollution, whereas the $G = (g_1 \quad \cdots \quad g_m)$ represent "supply chain" pollution. The Hadamard Product of *E* and *V* (the vector of value-added by industry) gives the gross pollution consequence from final production, by industry. (Note that this corresponds to the *GED* reported in: Muller, Mendelsohn, Nordhaus, 2011; Muller, 2013; 2014a; 2014b)

$$D_4 = V \cdot E$$

Matrix H_2 is the environmental pollution analog to A_2. Note that H_2 is defined in terms of the pollution damage vectors previously defined (D_1, D_2, D_3,D_4) as well as $D_5 = D_1 +$

D_4.Thus, H_2 represents the full or complete environmental counterpart to the NIPA I-O table, A_2. Here, *GED* is the sum of value-added pollution which is equal to the sum of pollution consequences from final demand.

$$H_2 = \begin{pmatrix} g_1 a_{1,1} & \cdots & g_1 a_{1,n} & D_{2,1} & g_1 h_1 & D_{3,1} \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ g_m a_{m,1} & \cdots & g_m a_{m,n} & D_{2,m} & g_m h_m & D_{3,m} \\ D_{1,1} & \cdots & D_{n,1} & & & \\ D_{4,1} & \cdots & D_{n,4} & & & GED \\ D_{5,1} & \cdots & D_{n,5} & & & \end{pmatrix}$$

b. Imports, Exports, Private Fixed Investment, and Inventory.

Although A_2 and H_2 are comprehensive, the following decomposes final demand into a more explicit accounting of its component parts. That is, balancing the I-O tables also requires accounting for imports to the system, exports from the system, capital accumulation, and changes to private inventory. Each of these flows has pollution consequences. Tracking these flows in an I-O context for all sectors is an important contribution of the present analysis.

Imports reduce (domestic) pollution in the sense that if imports are not accounted for, pollution from commodity use and some portion of personal consumption is attributed to domestic output, incorrectly. Exports must be added back to the system because, by definition, they do not appear as commodity use or final consumption in the I-O accounts. Similarly, private fixed investment is not consumed by industry or households, yet it does reflect production, and the pollution consequence must be tracked. Finally, changes in private inventory may either reduce pollution flows (since withdrawals of inventory represent consumption from prior production) or increase flows if inventories are built up.

These additional aspects of the I-O system are amenable to representation in tabular form as shown in *H*₃.

$$H_3 = \begin{pmatrix} g_1 a_{1,1} & \cdots & g_1 a_{1,n} & D_{2,1} & g_1 h_1 & g_1 I_1 & g_1 PFI_1 & g_1 Inv_1 & g_1 S_1 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ g_m a_{m,1} & \cdots & g_m a_{m,n} & D_{2,m} & g_m h_m & g_m I_m & g_m PFI_m & g_m Inv_m & g_m S_m \\ D_{1,1} & \cdots & D_{n,1} & & & & & & \\ D_{4,1} & \cdots & D_{n,4} & & & & & & GED \\ D_{5,1} & \cdots & D_{n,5} & & & & & & \end{pmatrix}$$

where: I_1 = net imports of commodity (1).
PFI_1 = private fixed investment of commodity (1).
Inv_1 = change in private inventory of commodity (1).
S_1 = total commodity output of commodity (1).

c. Characterizing pollution intensity.

In prior research, authors have measured pollution intensity of output as the ratio of pollution damage to value-added (*E*, above) or gross output (*G*, above), (see Muller, Mendelsohn, Nordhaus, 2011; Muller, 2013; 2014a; 2014b). Thus: $I_1 = \left({D_4}/{V}\right)$, and $I_2 = \left({D_4}/{C}\right)$, both of which are vector valued. With the machinery developed above, we are equipped to characterize additional measures of pollution intensity. The measure I_3 is defined as the ratio of the damage due to final production by industry (j) to the damage due to commodity use of the 1 through m commodities by industry (j). Hence, this is the ratio of "end-of-pipe" pollution to "supply-chain" pollution.

$$I_3 = \left({}^{D_4}/_{D_1} \right)$$

Note that I_3 is vector-valued; the vector characterizes the ratio for each industry (1 through m).

The next measure of pollution intensity shows the ratio of damage due to final production by industry (j) to the damage due to consumption of commodities produced by industry (j), when consumed by all industries (1 through m).

$$I_4 = \left({}^{D_4}/_{D_2} \right)$$

Additional measures of pollution intensity are reported that depict the share of pollution damage, by sector, by year, due to household consumption, exports, private fixed investment, changes to inventory and government consumption

III. Empirical Model and Data.

Section III. consists of two parts. Part III.a. describes the integrated assessment model used herein. This section describes data sources for the model itself, and how the model is applied to estimate air pollution damage. Section III.b centers on the USBEA data sources and how these I-O data are employed in the present analysis.

a. Empirical Integrated Assessment Model.

Air pollution damages are estimated using the AP2 integrated assessment model (IAM), (Muller, 2011; 2012; 2013; 2014a; 2014b; Holland et al., 2015; Jaramillo and Muller, 2016). AP2 is an updated version of the APEEP model (Muller and Mendelsohn, 2007; 2009; Muller, Mendelsohn, Nordhaus, 2011; NAS NRC 2010; Michalek et al., 2011). The model connects emissions to final monetary damage through five modules: emissions, air quality modeling and concentrations, exposures, physical effects, and monetary damage. AP2 encompasses five air pollutants: ammonia (NH_3), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2) and volatile organic compounds (VOCs).

AP2 begins with the USEPA National Emission Inventory (NEI) for a particular year; in the case of the present paper, either 1999 or 2011. These data are reported for specific sources and for spatially aggregated (by county) area sources for emissions from entities that do not have an individually-monitored release point. AP2 allocates these emissions data by location and source type within the model's matrix-based structure. For example, all of the roughly 3,100 counties in the lower-48 states are treated as a source location (the population-weighted centroid of the county, to be specific) for the county-aggregated emissions reported by USEPA. For the individually reported point sources, AP2 subdivides these according to the height of the emissions release and plume rise, referred to as the effective height of emissions. For point sources with an effective height over 500 meters, AP2 models the emissions release by the reported latitude-longitude of the smokestacks. These 656 sources consist predominantly of electric generating units, with a few manufacturing facilities as well. For sources with an effective height between 250 and 500 meters, AP2 treats emissions as if they are released at the population-weighted county centroid of the county containing the source (according to USEPA's NEI). And a similar approach is applied to all remaining point sources. The key distinction here is that the model recognizes that emissions move across the landscape differently as a function of their effective height of emission release.

With emission allocated in AP2, the next stage is the air quality model which translates emissions into ambient concentrations. These are estimated annual, county means. For a full description of the air quality model in AP2 see (Muller and Mendelsohn, 2007, or Muller, 2011). The air quality model is based on a source-receptor matrix framework, in which each cell of the matrix, denoted $T_{s,i,j}$, corresponds to the change in annual average concentrations of pollutant (s), emitted by source (i), in receptor county (r). There are distinct matrices in AP2 for the emitted pollutants (listed above). In addition, the model tracks cross-pollutant elasticities. For example, emissions of SO_2 contribute to ambient concentrations of $PM_{2.5}$ through atmospheric processes approximated in AP2. Secondary $PM_{2.5}$ formation is tracked for emissions of NO_x, NH_3, and VOC as well. Further, the model estimates the consequences of NO_x and VOC emissions on O_3 formation. (For statistical tests regarding the accuracy of AP2 air pollution concentration estimates, see Jaramillo and Muller, 2016).

With air pollution concentration estimates, by county, the model estimates exposures of sensitive receptor populations by using detailed county-level data covering: human populations, by age group, agricultural crop yields, timber yields, and man-made materials that are sensitive to accelerated depreciation due to exposure to acidic compounds found in common air pollution conditions. In order to translate exposures into physical effects, the model uses concentration-response functions; these are peer-reviewed estimates of the functional relationship between ambient concentrations and some physical symptom of exposure. In terms of the magnitude of damage, the most significant relationship is that between exposure to $PM_{2.5}$ and adult mortality rates. This study uses the results reported by C. Arden Pope et al., (2002), which is common in the literature that estimates air pollution damage (USEPA, 1999; Muller and Mendelsohn, 2007; 2009; 2012; H. Spencer Banzhaf and B. Andrew Chupp, 2012). For the O_3-mortality relationship, the findings from Michelle L. Bell et al., (2004) are used. For all complete list of the concentration-response functions used see: Muller and Mendelsohn, 2007 or Muller, 2011. Baseline incidence data are provided by the Center for Disease Control (CDC), (CDC Wonder, 2013).

With physical effects estimated, the last step is to convert the various effects into their money value equivalents. For adverse consequences that manifest in markets, reported prices are employed. So, for crop and timber consequences, market prices by crop and timber type are used. Valuation is considerably more difficult and contentious for services that are not traded in markets. Of particular importance is the value attributed to mortality risk. This study uses the Value of Statistical Life (VSL) approach to valuation (W. Kip Viscusi and Joseph E. Aldy, 2003). Briefly, the VSL is an estimate of the trade-off that society makes between mortality risk and money. VSL's are estimated in (typically) one of two contexts: in the labor market via compensating wage differentials and on surveys in contingent valuation frameworks. The $6 million VSL used herein is a standard choice for U.S. based studies and regulatory impacts analyses (USEPA, 1999; 2010). An alternative $2 million VSL is used in the sensitivity analysis.

i. Marginal Damages Algorithm.

AP2 is used to compute marginal damages on a dollar-per-ton basis for every source and every pollutant in both data years for a total of nearly 100,000 iterations of the model. The algorithm described in Muller and Mendelsohn (2007; 2009), and subsequently employed in Muller, Mendelsohn, and Nordhaus (2011) is invoked herein. This entails, for each data year, take 1999 as an example, estimating baseline damages due to reported baseline emissions, for all pollutants, damage endpoints, and all receptor counties, summed up into a scalar value. Then one ton of one pollutant is added to a particular source. Damages are totaled again in this "add-one-ton" scenario. The difference between the baseline case and the add-one-ton case comprises the monetary marginal damage for the chosen source and pollutant in 1999. This process is then repeated for the next source-pollutant pair and through all of the remaining possible source and pollutant combinations for 1999 and then 2011. Total pollution damage is computed by multiplying the marginal damage times reported emissions, matched by year, pollutant, and source.

ii. Data.

The data employed in this paper are many and varied. Section III.a. has described the data used in the AP2 model itself. This section focuses on the data used to invoke I-O techniques. Beginning broadly, the analysis employs the USBEA I-O data for 1999 and 2011. In order to characterize intermediate and final demand, the *USBEA I-O Use After Redefinitions table* spanning 1997 through 2012 for 69 industries is employed (USBEA, 2014a). This table reports the money value of commodity use by industry, government, and personal consumption. The table also reports: exports, private fixed investment, the and the change in inventory. Each of the "destinations" for current period consumption (and associated pollution) are used in an effort to "balance" the pollution accounts. Next, the USBEA *Imports Matrix* (USBEA, 2014b) is used to deduct, from the *Use table*, the money value of imports, by sector and for personal consumption. Importantly, certain commodities are made by multiple and several industries. Thus, in order to attribute output (and associated pollution) to the correct producing sector, the paper relies on the *USBEA I-O Make After Redefinitions table* spanning 1997 through 2012 (USBEA, 2014c). Specifically, for commodity (i), not made by industry (i), perhaps (j), the paper deducts the money value of this secondary production from total commodity use (i) and attributes the value to commodity use for (j). Thus, total value balances with the USBEA accounts, but is re-allocated to the industry (j) producing the commodity.

iii. NAICS Codes in USBEA and USEPA Data.

Attempts to reallocate production are motivated by the inherent differences in how market production and pollution emissions are attributed to industrial sectors by USBEA and USEPA, respectively. In a number of settings, the NAICS codes attributed to particular sources by these two agencies differ. For example, USBEA attributes the output from power plants owned and managed by the Tennessee Valley Authority (TVA) to the federal government (2-digit NAICS = 92), whereas the USEPA affixes such sources to the utility sector (2-digit NAICS = 22). Since total pollution output and damage are estimated exogenously to the I-O accounts via the USEPA NEI and the AP2 model, I modify the USBEA accounting for NAICS attribution to the USEPA's approach to the extent possible.

Two additional examples of the NAICS discrepancies are sectors 61 (education services) and 62 (health care services). Both sectors generate non-negligible pollution primarily through on-site power, steam, and heat production. For publicly-owned universities (sector 61) and hospitals (sector 62), the USBEA codes output as 2-digit NAICS = 92. In contrast, the USEPA employs NAICS = 61, and NAICS = 62, respectively.

iv. Imports, Exports, Private Fixed Investment, and Inventories.

Imported goods and services are accounted for by deducting consumption of imports from the *Use* matrix. Since estimating the pollution content of imports is well beyond the scope of the present analysis, no attempt is made to quantify the pollution damage (embodied) in imports. (See Arik Levinson, 2009 for a discussion of the pollution content of imported manufactured goods.)

In contrast, pollution damage due to exports of commodities is explicitly accounted for. That is, exports enter the *Use* matrix for each commodity. Estimating pollution damage from exports amounts to multiplication of the pollution content coefficients $(g_1,\ldots g_m)$ by the gross export value for each commodity. This approach is also applied to private fixed investment and changes in inventories. Note that private fixed investment (accumulation of capital) corresponds to current period production that is not sold to or consumed by other industries, households, or exported. Hence, pollution is produced, and is accounted for by computing the product of the value of fixed investment and the $(g_1,\ldots g_m)$ vector. Changes in inventories may correspond to sales of commodities produced in earlier periods (values less than zero in the *Use* matrix) and additions to inventories through current period production. Pollution damage from each case is estimated by using the $(g_1,\ldots g_m)$ vector. However, inventory drawdowns are deducted from current period pollution damage since production of existing inventories occurred in an earlier period. Thus, the money value of pollution damage from commodities made in some earlier periods is deducted from total damage from commodity output in the current period.

v. Remaining Discrepancies.

Remaining discrepancies between the sum of intermediate consumption, final demand, exports, private fixed investment, changes in inventories, less imports are inevitable for some sectors. Although both the USEPA NEI and the USBEA I-O data are the best available estimates of pollution output and flows of commodities, respectively, these data are not, and cannot be interpreted as, completely accurate census measurements. The USEPA NEI does consist of measured pollution for point sources with continuous emission monitoring systems (CEMS), but it is comprised of estimated pollution output for the balance of sources. Similarly, the USBEA I-O is not based on a comprehensive census of all firms and establishments, but rather from a sample. This is not intended as a criticism of either agency; rather, this serves as one explanation for the imperfect balance between the pollution damage estimates derived by adding that from intermediate consumption, final demand, exports, private fixed investment, and changes in inventories (less imports) and the damage estimates directly from the USEPA NEI.

IV. Results.

This section of the paper begins with a discussion of summary statistics covering changes in pollution and market output by sector, as well as the share of GED contributed by each sector. Next, the analysis focuses on 5 of the top polluting sectors and the most polluting inputs consumed by each. Various measures of pollution intensity are then reported. Then the composition of air pollution damage is explored by reporting shares of damage from: private fixed investment, household consumption, changes to inventory, government consumption and private sector input use. Finally, the analysis compares damages from exported goods produced domestically and avoided damages due to imports.

a. Summary statistics and stylized facts.

Table A.2 (in the appendix) presents some stylized facts regarding changes in output and pollution between 1999 and 2011. The vast majority of sectors (15 out of 19) exhibit falling GED; only wholesale trade, finance, management, and accommodation and food services produce greater GED in 2011 than in 1999. Within these sectors, only accommodation and food services produces a significant share of GED (over 3% in 2011). Conversely, the VA of 16 out of 19 sectors expanded between 1999 and 2011. Output in construction, utilities, and other services declined. Summarizing the left-hand panel of table A.1, most industries expanded in terms of market output while simultaneously reducing their pollution output. Hence, pollution intensity fell.

The right-hand panel of table A.1 shows the share of total GED contributed by each sector. Generally, the sectors that comprise large shares of economy-wide GED have had their fractions of total GED remain relatively stable. For example, utility GED amounted to nearly 32% of total GED in 1999 and just under 31% of GED in 2011. Manufacturing produced almost 17% of GED in 1999 and slightly more than 15% of GED in 2011. Similarly, agriculture GED amounted to 18.6% of GED in 1999 and just over 20% of GED in 2011. These findings speak to the stability of the composition of

GED across sectors from 1999 to 2011. However, some sector shares did change appreciably. For example, the waste management sector produced 9.5% of total GED in 1999 and 5.5% of GED in 2011. Accommodation and food services generated 0.8% of GED in 1999 but the share from this sector increased to over 3% in 2011. GED from the transportation sector also increased as a share of total GED by over 2 percentage points.

b. Input-Output Analysis of the Top Five Polluting Sectors.

Table 1 provides a more detailed analysis of the five sectors that generated the greatest pollution damage in both 1999 and 2011. The table reports damages from input use (this is denoted D_1 in the conceptual model and in table 1) and value-added production (denoted D_4). For each polluting sector, the table reports damages from the top-five inputs (ranked according to the amount of damage generated by their use) for each of the five sectors. So, in 1999, value-added damage production (D_4) from the agriculture/forestry sector amounted to about $110 billion. Total damage from the use of inputs by the agriculture and forestry sector amounted to $29 billion. The input use that generated the greatest environmental pollution damage was also agriculture/forestry. (This heavy reliance on intra-sector inputs likely stems from production of feed to grow livestock.) This sector also relied heavily on output from the utility sector, and to a markedly smaller extent, on manufacturing, transportation, and mining and oil and gas extraction products. Hence, intra-sector input use contributed over 80 percent of damage from inputs. Damages from value-added production were three-times greater than the damages from input use.

The utility sector produced pollution damage from value-added production that totaled $184 billion in 1999. Damages from input use amounted to just $9 billion. Damages from value-added production were roughly twenty-times greater than from inputs. The greatest contributor to input damages for the utility sector was mining and oil and gas extraction. This sector comprised half of input damage. This should be intuitive given that air pollution from utilities is mostly due to electric power generation and, in 1999, most of the power produced in the U.S. was the result of burning coal, natural gas, and oil. Transportation also was an important component of input damage. Bulky fossil fuels (coal and oil) are transported by rail, pipeline, and barge from refineries and mines to power plants for use. (Natural gas is predominantly moved via pipeline.) These shipments rely of combustion of fossil fuel for power which creates air pollution damage. Intra-sector consumption of inputs was also a significant source of input damage for utilities.

The manufacturing sector produced damages from value-added production that were less than damages from input use: $98 billion from value-added production relative to $171 billion from input use. This stands in contrast to each of the other sectors in table 1. Top among contributors to input damage was the agriculture and forestry sector. Inputs from this sector employed by manufacturers include forest products used in the production of paper and wood products as well as grains and other agricultural products used to make food products. Damage from input use from the agricultural/forestry sector amounted to over one-third of all input damage for manufacturing. Consumption of inputs from the utility sector also contributed a significant share. This is not surprising given that manufacturers require electric power. Intra-sector damages were an important source of damage. Nearly 22 percent of input damage came from the use of inputs produced by the manufacturing sector. The mining and oil and gas extraction sector along with transportation contributed the next largest shares of input damages in 1999.

The transportation sector generated air pollution damages of about $55 billion through value-added production. The waste management sector produced about $57 billion. Damages from input use in both sectors amounted to a much smaller figure than did value-added production. For transportation, input damages were about one-fifth the value of damages from value-added production. For waste management, input damages totaled just about 15 percent of the damages from value-added production.

For 2011, table 1 indicates that, first and foremost, pollution damages fell both in terms of input use and value-added production. This supports the findings previously reported from table A.1. Second, with a few exceptions, the top contributors to input damages across these sectors remained the same. Notable exceptions to this pattern include the appearance of damages from the use of inputs produced by the construction sector by agriculture/forestry and transportation sectors. In addition, the damages from the use of inputs created by the food services and accommodations sector by the administration and waste management sector[4] also did not show up in the list for 1999. In addition, only the manufacturing sector exhibited damages from value-added production less than the damages from input use.

c. Changes in sectoral structure: Inputs, outputs, inside and beyond the market boundary.

Table 2 reports changes in two measures of industrial structure in terms of market output and pollution output. The left-hand panel of the table shows annualized changes in VA and input use, by sector. The right-hand panel displays annualized rates of change for GED from VA production (D_4) and the pollution damage from input use (D_1). Table 2 facilitates an assessment of verticalization at the sectoral level. In terms of the market accounts, a sector is verticalizing if the value of input use increases slower than VA. The left-hand side of table 2 shows that the agriculture sector shows evidence of verticalization as input use increased by just 0.4 percent, per year, while VA expanded by over 3.2%. Conversely, manufacturing is de-verticalizing since input use increased at a 2.6% annual rate, while VA grew by 1.7%, per annum. In summary, table 2 shows that seven sectors are verticalizing and the remaining twelve are de-verticalizing.

[4] This particular result bears some discussion as it highlights a shortcoming of the sector level of analysis. Within the administration and waste management sector is the travel arrangement service industry. Within the food- service and accommodation sector are hotels. There is an obvious link between these two industries. However, most of the air pollution damage from waste management comes from incineration, waste collection, and landfills. The bulk of air pollution damage from food service and accommodation comes from restaurants. Because the analysis attributes all industries within a sector the same pollution technical coefficient, some misappropriation inevitably occurs as is the case for travel services and hotels.

The right-hand side of table 2 facilitates an assessment of pollution verticalization. In order to assess whether sectors are verticalizing with respect to pollution output, GED from VA production is compared to damage from input use. Evidence of pollution verticalization manifests if the share of monetary damage from VA production increases relative to that from input use. Conversely, a sector is de-verticalizing if monetary pollution damage from inputs increases relative to damage from VA production. Table 2 shows that, for fifteen sectors, the air pollution impacts from input use fell more rapidly than (or increased slower than) GED from VA production. This is evidence of pollution verticalization.

The four sectors exhibiting signs of pollution de-verticalization are: manufacturing, professional, scientific, and technical services, health care, and other services. Among these, only manufacturing is a significant contributor of air pollution damage. This results comports with the aggregate (D_1) and (D_4) measures reported in table 1. The annualized rate of reduction in (D_4) from $97 billion to $38 billion exceeds that for (D_1) which in absolute terms fell from $171 billion to $79 billion.

Taken together, the market and pollution accounts shown in table 2 suggest that there is little evidence of a correspondence between market and pollution de-verticalization. Roughly one-half of all sectors showed evidence of market de-verticalization while just one-fifth of all sectors exhibit pollution de-verticalization. However, three-fourths of the sectors that underwent pollution de-verticalization were also de-verticalizing in terms of market output.

Insights with respect to the “causes”, or reasons, for some sectors verticalizing in the market accounts and de-verticalizing in the pollution accounts come from the I-O tables in the appendix (see tables A.2 and A.3). Using retail trade as an example of a sector that exhibited pollution verticalization and market de-verticalization, table A.2 reveals that, in 1999, 60 percent of input pollution damage was due to consumption of utility output. This was likely demand for electric power. Table 2 indicates that damages from VA production in the utility sector fell by over 8 percent annually. The next largest source of input damage to retail trade was the waste management sector. Damages from this sector declined by nearly 9 percent per annum. Hence, two major sources of supply chain damage to retail trade showed a more rapid rate of attenuation than the damages from VA production. This pattern drives pollution verticalization in the retail trade sector.

More generally, there appear to be two possible explanations for pollution verticalization. One reason is that inputs used by particular sectors have become cleaner. An alternative explanation is that firms substitute among inputs toward less pollution intensive factors of production. The results for the retail trade sector suggest the former; the same inputs are being used, their pollution content is falling.

d. Measures of Pollution Intensity.

Table 3 displays four measures of pollution intensity. The first two columns report conventional measures of pollution intensity: the ratio of GED to VA (I_1) and the ratio of GED to gross output (I_2). (These correspond to the pollution technical coefficients *E* and

G discussed in section II., respectively.) Both are expressed in nominal terms. Beginning with GED/VA (I_1), in 1999 both utilities and agriculture produced GED that exceeded their reported VA. No other sector generated GED that was even close to this level – relative to VA – in 1999. Specifically, the damages produced by the mining and waste management sectors amounted to roughly one-quarter of VA. Transportation GED was less than one-fifth of its VA in 1999.

Many sectors had their GED/VA ratios fall precipitously between 1999 and 2011. Agriculture GED fell from 120% of VA in 1999 to 40% in 2011. The utility sector GED dropped from 104% of VA in 1999 to 43% in 2011. The mining and waste management sector GED/VA ratios fell to less than 0.05. Some of the largest GED-producing sectors showed less vertiginous reductions in pollution intensity. The manufacturing sector GED/VA metric declined from 0.065 to 0.03. Construction GED comprised 9.5% of VA in 1999 and 5.6% of GED in 2011.

The only sector showing higher levels of the (I_2) measure of pollution intensity in 2011 than in 1999 was accommodation and food services. For the economy as a whole, pollution intensity dropped from 7.1% of VA to 2% of VA between 1999 and 2011.

The second column of table 1 shows that the GED/GO (I_2) ratios were (i) lower than the GED/VA ratios which is expected given the relationship between VA and GO, and (ii) fell from 1999 to 2011, akin to the GED/VA metric. For the total economy, GED amounted to 3.8% of GO in 1999 and 1.6% of GO in 2011.

Although it is obvious that GED/VA will exceed GED/GO, the degree to which these metrics differ is the first glimpse into the pollution damage generated by the consumption of inputs relative to final (VA) production. For example, the transportation sector GED/VA ratio in 1999 was 0.189 and the GED/GO measure was 0.097. This implies that VA was about one-half the magnitude of GO. In contrast, the manufacturing sector GED/VA ratio was 0.065 in 1999 and the GED/GO metric was 0.024. Thus, VA is roughly one-third of manufacturing GO. Alternatively, the inputs to manufacturing comprise a larger share of the total value of output than do the inputs to transportation. The next step in the analysis explores how the value of inputs and outputs change, by sector, both in terms of the market and pollution values.

Table 3. reports two additional measures of pollution intensity. Recall that (I_3) is the ratio of GED from VA production to pollution damage from input use, by sector. This measures the relative contributions of VA damages and supply chain damages. The most striking result with respect to I_3 is for the utility sector. In 1999, damage from VA production by the utility sector was over twenty-times larger than the damages from use of inputs by the utility sector. This ratio increased to over 54 in 2011. Hence, in both 1999 and 2011, damages due to VA production by the utility sector exceeded damage due to inputs used by the utility sector to a degree unparalleled by the other sectors in the economy. This finding makes sense. Most of the damages from utilities accrue from burning fossil fuels to make power. Thus, minimally processed inputs (raw coal and natural gas) are burned to make an output which is then consumed by other industries

and households. Aside from extraction and transport, inputs to production don't produce much in the way of air pollution. In contrast, the production of electricity yields copious amounts of emissions.

The next largest ratio manifests for the waste management sector; in 1999 VA production generated over seven times more damage than inputs used by that sector. The ratios for the transportation and mining sectors were over 4, while that for the agriculture and construction sectors was over 3. Notably, the manufacturing sector ratio was just 0.65. Hence, pollution damage from inputs to the manufacturing process exceeded that from VA production[5].

In summary, twelve sectors in 1999 generated less GED from VA production than pollution damage stemming from inputs. Six of these sectors generated GED that was less than or equal to 5% of pollution damage from inputs. Eleven of these sectors also had a ratio of less than one in 2011; only food service and accommodation increased above unity in 2011.

The next column in table 3 displays the (I_4) ratio which relates GED from VA production from each sector (i) to the pollution damage from other sectors' (j not equal to i) use of commodities produced by (i). If all output was consumed by other industries as inputs I_4 would equal unity. Therefore, if I_4 for sector (i) is greater than one, output for (i) is consumed by entities other than other firms. These may include households,

[5] The I_3 results for agriculture, utilities, manufacturing, transportation, and waste management can also be deduced from table 1.

governments, or exports in addition to private fixed investment. Conversely, if I_4 for sector (i) is less than one, the sum of damages due to input use of sector (i) output exceeds sector (i) GED. This means that inputs are being obtained from sources other than domestic firms in (i): such as drawdowns to inventories and imports.

In 1999, just three sectors displayed an I_4 ratio of less than one: professional, scientific, and technical services, mining and oil and gas extraction, and construction. (Since only mining and construction are significant sources of air pollution these two sectors are explored here.) For mining and oil and gas extraction, imports largely explain this result: many domestic firms reliant on fossil fuels consumed imported products. Construction, on the other hand showed a large allocation of its output to private fixed investment (USBEA, 2014).

Among sectors with an I_4 measure greater than unity, four sectors show an I_4 ratio of greater than five in 1999: arts and recreation[6], retail trade, health care, and education. Emissions from education and health care are typically due to on-site heating and power generation. Such sectors, and industries within these sectors, produce output that is not pollution intensive when consumed, or used, by other sectors relative to the GED they generate in VA production. Most of the other sectors show an I_4 ratio between one and five. For example, the utility sector I_4 ratio was 1.7 in 1999 and 1.9 in 2011. Thus, damage from VA production is between one and two-times pollution

[6] Air pollution damages from this sector are mostly due to emissions from marinas (Muller, Mendelsohn, Nordhaus, 2011).

damage emanating from use of commodities by other sectors. Manufacturing had a similar I_4 ratio.

In 2011, all sectors displayed an I_4 ratio in excess of one. The most significant differences manifest in the mining and construction sectors, both of which move from less than one to greater than one from 1999 to 2011. While the construction sector still devoted a significant share of output to private fixed investment, total intermediate use doubled in real terms between 1999 and 2011. In terms of mining and extraction, domestic production of oil and gas expanded significantly between 1999 and 2011. All else equal this implies greater intermediate use by domestic firms.

e. Decomposition of Pollution Damage.

Table 4 reports the share of damages occurring due to production in 1999 that: satisfied private and government intermediate demand, met household demand, went to private fixed investment, and affected changes in inventory. Economy-wide, the largest share of damage was from private intermediate demand for inputs. This amounted to 56 percent of total damage. The next largest component of pollution damage, about 25 percent of the total, was due to production that satisfied household consumption. Government intermediate demand and private fixed investment accounted for about 7 percent of damage each. Changes to inventory contributed a very small share of total damage.

Table 4 also shows the decomposition of pollution damages for each sector. For example, nearly 80 percent of agricultural pollution damage was due to production that satiated private intermediate demand, while just 15 percent was due to household consumption. Mining pollution costs showed a different mix: 80 percent of damages were due to private intermediate demand and 13 percent of damage was from production targeted to private fixed investment. Like mining, about 80 percent of waste management damages were due to private intermediate demand. Utility pollution damage was more equally split between intermediate demand and household consumption. Manufacturing damage was due to about 50 percent of output allocated to private intermediate demand, 20 percent for household consumption, and 12 percent to private fixed investment. The mix of transportation damage was quite similar to manufacturing. In contrast, sectors such as food services, health care, entertainment, and retail trade were almost entirely due to personal consumption.

Table 5 is analogous to table 4, focusing on the year 2011. The results, in terms of damage shares to private and government intermediate demand, personal consumption, private fixed investment, and inventories are quite similar to 1999. Among the heavy-polluting sectors, manufacturing, transportation, waste management, and agriculture exhibited very similar shares to 1999. Some notable differences include a larger share of construction damage due to government demand for inputs. This was likely due to policies exhibiting demand for construction services for the purpose of stimulation. Utility damages were tilted more toward household consumption in 2011. External costs from mining production targeted to private fixed investment increased from 13 percent of total damage to over 20 percent. This may reflect investment in capital used for oil and gas extraction.

Table 6 reports the pollution damage intensity of exported goods and the avoided damages from imported goods. To calculate avoided damages from imports, the value of imported goods *that would have been produced by firms in sector (i), and then used by firms in sector (j)* is multiplied times the domestic pollution technical coefficient for sector (i). The left panel of table 6 indicates that in 1999, only imports in three sectors avoided damages that amounted to more than 5 percent of realized damages from domestic production. The largest of these was in the mining and oil and gas extraction sector. Had all imports been produced domestically, pollution damage due to production in this sector would have been 43 percent higher. Manufacturing shows a similar result. Had all imported goods in the manufacturing sector been made in the U.S., the pollution damage from this sector would have been 23 percent larger. For the agriculture sector, damages would have been nearly 10 percent higher had all imported products been produced domestically. In terms of exports in 1999, goods sold overseas produced by firms in the manufacturing sector comprised the greatest share of pollution damage. Damages from the production of exported goods amounted to over 13 percent of total damage from manufacturing. Exports of goods in the wholesale trade sector (likely refined petroleum products) amounted to over 8 percent of damage from that sector.

In 2011, imports in the same three sectors resulted in the avoidance of damages over five percent of total (sector damage). The largest again was in mining and oil and gas extraction. Damages would have been almost 70 percent higher has all imported goods been produced domestically. Manufacturing damages would have been 30 percent higher, and agricultural damages would have been nearly 12 percent greater had all imported goods been made in the U.S. The magnitude of avoided damage due to imports remained basically constant from 1999 to 2011.

In contrast, the share of damages from goods targeted for export increased from 1999 to 2011 for many sectors. For the economy as a whole, production of exports amounted to about 5 percent of total damage in 1999 and almost 10 percent in 2011. Particularly large changes in the share of sectoral damage from exported goods were evident in the following sectors: mining and oil and gas extraction, agriculture and forestry, and manufacturing.

V. Conclusions.

This analysis builds on prior work in the area of environmentally-extended input-output analysis (EEIO) by estimating a series of monetary pollution accounts that track the value flows of pollution damage in the U.S. economy for 1999 and 2011. Several contributions are novel. First, the paper uses state-of-the-art environmental and economic modeling to provide the first value-based EEIO of the U.S. economy since the work of Matthews and Lave (2000) which relied on data now 23 years old. The analysis goes beyond intermediate demand and value added production to estimate damage coming from personal consumption, exports, government intermediate demand, private fixed investment, and changes to inventories. The inclusion of two data years reveals a precipitous reduction in pollution intensity in the U.S. economy. Though earlier work has provided some evidence of this (Muller, 2014a; 2014b) the present analysis shows different rates of change in pollution intensity for value-added production and the consumption of inputs. The inter-temporal framework also reveals stability in sector level input-output pollution flows.

Perhaps the most fundamental contribution of the work lies in the pursuit of monetary pollution I-O accounts. The importance of going beyond physical accounts that track emissions and consumption of natural resources is two-fold. One, this tack encompasses or reflects the significant heterogeneity in the "prices" attributed to emissions. That is, prior research indicates that the damage from a unit of local air pollution emissions varies significantly according to where it is emitted (Fann et al., 2009; Muller and Mendelsohn, 2009). If an EEIO model only tracks emissions (as much of the published literature does) all tons are attributed equal weight. This approach diverges from what is known about the value of such emissions. In addition, the only prior monetary EEIO model for the U.S employed national average pollution "prices" (Matthews and Lave, 2000). Thus, the same criticism stands. Second, the use of monetary EEIO accounts is more amenable to a synthesis of market and environmental accounting structures. If the goal is such a synthesis, then monetary EEIO is clearly preferable to physical accounting models.

Several caveats are worth pointing out. IAMs of the type employed here introduce considerable uncertainty into the EEIO system. Key sources of uncertainty include: the modeled connection between emissions and concentrations, the effect of exposure to fine particles on mortality rates, and the value attributed to mortality risks. The latter two are not specific to any particular IAM. These sources of uncertainty are inherent in any attempt to estimate pollution damage. The first source, however, is particular to the IAM used. In light of this, it is worth noting that the ability of the AP2 model to reliably connect emissions to ambient concentrations is documented in prior work (Muller, 2011; Jaramillo and Muller, 2016). Largely left unexplored is a more formal treatment of uncertainty throughout the different modules of the IAM. Monte Carlo simulations are left for future work.

The focus on sectoral-level I-O modeling misses intra-sector variation in pollution intensity of output. As mentioned above, all industries within a sector are attributed the same pollution technical coefficient. This overlooks considerable variation in pollution intensity across industries within a sector (Muller, Mendelsohn, and Nordhaus, 2011). Employing the sector level of analysis also yields some counterintuitive results such as the large input damages from food and accommodation services due to use by firms in the waste management and administrative services sector. The sectoral approach is pursued in this analysis in order to demonstrate the EEIO method in a manner that is both comprehensive across all sectors and yet of small enough dimension to be manageable. A direction for further research would decompose the sectoral results, perhaps within the manufacturing sector, to explore a more detailed EEIO set of accounts.

Building on prior work, this analysis demonstrates that monetary EEIO modeling is feasible in the U.S. and likely in other developed economies. Although the decision to create formal, government-sanctioned environmental accounts is fraught with political and bureaucratic obstacles, the present analysis demonstrates both the feasibility and value of such an exercise.

Tables.

Table 1. Pollution Damages Due to Input Use and Value-Added Production from Top Five Polluting Sectors.

1999									
Agriculture /Forestry		**Utility**		**Mfg.**		**Transportation**		**Admin. Services & Waste Manage.**	
Input type	**D_1**	**Input type**	**D_1**	**Input type**	**D_1**	**Input type**	**D_1**	**Input**	**Input type**
Ag. /For.	24,010[A]	Mining & OGE[B]	4,716	Ag. /For.	63,616	Trans.	4,948	Admin. & Waste	3,597
Utility	3,393	Trans.	1,900	Utility	39,676	Admin. & Waste	2,976	Utility	2,132
Mfg.	962	Utility	1,549	Mfg.	36,180	Utility	1,999	Trans.	936
Trans.	751	Admin. & Waste	559	Mining & OGE	15,112	Mfg.	1,372	Mfg.	533
Mining	134	Mfg.	219	Trans.	8,724	Mining & OGE	281	Ag. /For.	116
Sum of D_1	29,396		9,145		170,622		11,890		7,625
D_4	110,000		184,000		97,700		54,900		56,700
2011									
Input type	**D_1**	**Input type**	**D_1**	**Input type**	**D_1**	**Input type**	**D_1**	**Input**	**Input type**
Ag. /For.	12,768	Mining & OGE	573	Ag. /For.	40,848	Trans.	3,618	Admin. & Waste	942
Mfg.	618	Trans.	446	Mfg.	14,525	Mfg.	1,316	Trans.	482
Utility	532	Utility	225	Utility	8,502	Utility	817	Mfg.	353
Trans.	352	Admin. & Waste	168	Mining & OGE	7,943	Admin. & Waste	636	Utility	257
Constr.	47	Mfg.	146	Trans.	4,868	Constr.	86	Food/ Accom.	130
Sum of D_1	14,374		1,716		78,825		6,603		2,333
D_4	66,912		64,604		38,417		30,785		18,693

A = All values in real ($2000), millions.
B = Mining and Oil and Gas Extraction Sector.
D_1 = Pollution damage from input use.
D_4 = Pollution damage from value-added production.

Table 2: Secular changes in industry structure: annual rates of change in the monetary value of inputs and outputs.

	Market Accounts		Pollution Accounts	
Sector	VA	Input Use	GED (D_4)	Input Use (D_1)
Agriculture/Forestry	3.25	0.42	-4.07	-5.79
Mining	1.95	-5.62	-7.94	-9.34
Utilities	-0.36	-4.19	-8.36	-13.02
Construction	-2.48	-3.87	-4.91	-9.54
Manufacturing	1.70	2.61	-7.49	-6.23
Wholesale Trade	1.77	3.33	2.48	-7.43
Retail Trade	1.15	3.08	-5.48	-9.16
Transportation and Warehousing	1.30	2.79	-4.61	-4.78
Information	4.23	3.14	-4.68	-9.67
Finance and Insurance	2.53	2.37	0.45	-10.12
Real Estate and Rental and Leasing	2.34	2.64	-3.31	-3.93
Professional, Scientific, and Technical Services	2.50	1.49	-13.95	-8.18
Management of Companies and Enterprises	0.65	2.10	61.04	-3.57
Admin. Waste Mgmt. and Remediation Services	2.82	0.36	-8.84	-9.40
Educational Services	2.67	3.06	-4.94	-6.55
Health Care and Social Assistance	2.71	3.45	-8.66	-6.80
Arts, Entertainment, and Recreation	1.69	3.51	-2.14	-6.72
Accommodation and Food Services	0.98	1.46	5.17	-8.62
Other Services (except Public Administration)	-1.67	-0.15	-18.85	-7.51

Table 3: Nominal Measures of Pollution Intensity, by Sector, for 1999 and 2011.

	I_1 (E)		I_2 (G)		I_3 (D_4/D_1)		I_4 (D_4/D_2)	
Sector	**1999**	**2011**	**1999**	**2011**	**1999**	**2011**	**1999**	**2011**
Agriculture/Forestry	1.186	0.397	0.445	0.181	3.858	4.705	1.176	1.280
Mining	0.255	0.028	0.134	0.020	4.057	4.326	0.976	1.069
Utilities	1.040	0.427	0.615	0.297	21.71	54.051	1.734	1.942
Construction	0.095	0.056	0.047	0.030	3.479	6.509	0.941	1.011
Manufacturing	0.065	0.030	0.024	0.010	0.648	0.661	1.285	1.292
Wholesale Trade	0.001	0.001	0.001	0.001	0.059	0.179	1.488	1.486
Retail Trade	0.012	0.005	0.008	0.003	0.421	0.528	8.393	8.358
Transportation and Warehousing	0.189	0.098	0.097	0.046	4.760	4.940	1.346	1.284
Information	0.000	0.000	0.000	0.000	0.009	0.018	1.445	1.478
Finance and Insurance	0.000	0.000	0.000	0.000	0.001	0.002	1.649	1.721
Real Estate and Rental and Leasing	0.000	0.000	0.000	0.000	0.004	0.003	2.765	2.674
Professional, Scientific, and Technical Services	0.001	0.000	0.000	0.000	0.034	0.017	0.917	1.085
Management of Companies and Enterprises	0.000	0.000	0.000	0.000	0.000	0.001	1.043	1.003
Admin. Waste Mgmt. and Remediation Services	0.223	0.046	0.128	0.029	7.620	7.450	1.109	1.112
Educational Services	0.016	0.007	0.010	0.004	0.231	0.285	12.180	9.759
Health Care and Social Assistance	0.001	0.000	0.001	0.000	0.051	0.042	33.429	48.52
Arts, Entertainment, and Recreation	0.069	0.038	0.044	0.022	2.266	3.251	5.634	5.912
Accommodation and Food Services	0.026	0.041	0.010	0.016	0.427	2.151	3.841	4.813
Other Services (except Public Administration)	0.013	0.001	0.008	0.001	0.815	0.123	2.242	3.777
Total Economy	**0.071**	**0.020**	**0.038**	**0.016**				

Table 4: Composition of Pollution Damage in 1999.

All values expressed as share of total GED.

Sector	**Private Sector Commodity Use**	**Government Commodity Use**	**Personal Consumption**	**Private Fixed Investment**	**Change Private Inventory**
Agriculture/ Forestry	0.772	0.006	0.147	0	-0.003
Mining	0.812	0.033	0.001	0.125	-0.003
Utilities	0.512	0.066	0.419	0	0
Construction	0.085	0.226	0	0.689	0
Manufacturing	0.486	0.051	0.199	0.119	0.012
Wholesale Trade	0.459	0.037	0.296	0.117	0.007
Retail Trade	0.094	0	0.865	0.04	0
Transportation and Warehousing	0.558	0.059	0.246	0.033	0.003
Information	0.513	0.063	0.284	0.098	0.002
Finance and Insurance	0.568	0.016	0.394	0.005	0
Real Estate and Rental and Leasing	0.287	0.019	0.629	0.049	0
Professional, Scientific, and Technical Services	0.467	0.16	0.07	0.275	0
Management of Companies and Enterprises	0.906	0	0	0	0
Admin. Waste Mgmt. and Remediation Services	0.82	0.088	0.089	0	0
Educational Services	0.038	0.028	0.93	0	0
Health Care and Social Assistance	0.02	0.007	0.972	0	0
Arts, Entertainment, and Recreation	0.157	0.02	0.8	0.017	0
Accommodation and Food Services	0.229	0.018	0.751	0	0
Other Services (except Public Administration)	0.292	0.058	0.65	0	0
Total Economy	0.556	0.063	0.255	0.077	0.002

Table 5: Composition of Pollution Damage in 2011.

All values expressed as share of sector GED.

Sector	Private Sector Commodity Use	Government Commodity Use	Personal Consumption	Private Fixed Investment	Change Private Inventory
Agriculture/ Forestry	0.746	0.004	0.129	0	-0.016
Mining	0.698	0.033	0	0.213	0
Utilities	0.428	0.072	0.496	0	0
Construction	0.152	0.332	0	0.516	0
Manufacturing	0.452	0.069	0.223	0.074	0.007
Wholesale Trade	0.416	0.043	0.308	0.113	0.003
Retail Trade	0.088	0	0.879	0.033	0
Transportation and Warehousing	0.564	0.07	0.213	0.028	0.001
Information	0.465	0.068	0.321	0.094	0.001
Finance and Insurance	0.513	0.022	0.417	0.003	0
Real Estate and Rental and Leasing	0.311	0.018	0.622	0.027	0
Professional, Scientific, and Technical Services	0.448	0.191	0.067	0.253	0
Management of Companies and Enterprises	0.857	0	0	0	0
Admin. Waste Mgmt. and Remediation Services	0.794	0.113	0.09	0	0
Educational Services	0.04	0.028	0.923	0	0
Health Care and Social Assistance	0.012	0.006	0.981	0	0
Arts, Entertainment, and Recreation	0.14	0.025	0.808	0.018	0
Accommodation and Food Services	0.18	0.03	0.788	0	0
Other Services (except Public Administration)	0.23	0.037	0.733	0	0
Total Economy	0.500	0.076	0.294	0.061	-0.002

Table 6: Avoided Pollution Damage from Imports and Domestic Pollution Damage from Exports.

All values expressed as share of sector GED.

	1999		**2011**	
Sector	Avoided GED From Imports	Exports	Avoided GED from Imports	Exports
Agriculture/ Forestry	0.096[A]	0.077	0.117	0.136
Mining	0.434	0.032	0.684	0.057
Utilities	0.004	0.004	0.005	0.004
Construction	0	0	0	0
Manufacturing	0.234	0.132	0.309	0.176
Wholesale Trade	0	0.083	0	0.118
Retail Trade	0	0	0	0
Transportation and Warehousing	0.042	0.1	0.038	0.125
Information	0.006	0.041	0.008	0.053
Finance and Insurance	0.007	0.018	0.029	0.046
Real Estate and Rental and Leasing	0	0.016	0	0.022
Professional, Scientific, and Technical Services	0.019	0.027	0.045	0.041
Management of Companies and Enterprises	0	0.094	0	0.143
Admin. Waste Mgmt. and Remediation Services	0.003	0.002	0.003	0.003
Educational Services	0.001	0.004	0.005	0.008
Health Care and Social Assistance	0.002	0	0.002	0
Arts, Entertainment, and Recreation	0.002	0.006	0.002	0.009
Accommodation and Food Services	0	0.002	0	0.002
Other Services (except Public Admin.)	0.003	0	0.005	0
Total Economy	0.077	0.048	0.071	0.095

A = pollution damage from imports reflects the avoided damage from imported goods. Calculated as the value of imports times the pollution technical coefficient for goods from each sector when produced domestically.

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Appendix.

Any paper that explores environmental externality in the context of I-O relies, in some way, on the tools developed by Leontief (1970; 1985), who, in addition to pioneering I-O, also developed a synthesis between traditional economic I-O and external effects. An important distinction in the present approach to that of Leontief (1970) and the subsequent work by many additional authors (Hendrickson et al., 1998) is the following. Leontief (1970) worked with direct input requirement matrices (denoted A), and used A to identify the Leontief inverse $(I - A)^{-1}$ which enabled analyses focusing on changes in input use (x) corresponding to changes in final demand (y): $x = (I - A)^{-1}y$. In fact, most applications of environmental I-O to life cycle analysis (LCA) employ this basic structure (Hendrickson, Lave, Matthews, 2006).

The present analysis differs in that the USBEA "use" I-O tables are central to the analysis. Rather than direct requirement matrices, which show the dollar-value requirements of inputs needed to produce a dollar's worth of output, the use tables report actual usage of commodities by industries, in total. In effect, these are conditioned on observed final demand. This distinction facilitates an ex post assessment of pollution emissions and damage arising from both use of commodities and industry value added. The cost of this new approach is the inability to invert the requirements matrix to solve for inputs, conditional on final demand. However, this is not the thrust of the present paper as such exercises comprise well-trodden ground in the literature (Lave et al., 1995; Hendrickson et al., 1998; Hendrickson, Lave, and Matthews, 2006).

In order to clarify the distinction between the current work and prior research, this section explicitly draws out, or explains, the differences and innovations in the present work relative to the literature. In Hendrickson et al., (1998) a matrix comprised of pollution impacts, identified on the diagonal, is proposed. This matrix pre-multiplies a vector of input requirements for some industry (j) to estimate total pollution impact associated with commodity use by (j) in order to satisfy final demand. In contrast, the present paper proposes a matrix of pollution impacts from commodity use, *for all industries*, conditional of actual usage by industries. Coupled with the use matrix, the computation of gross, or total, pollution damage from *actual* output, and commodity consumption is straightforward: it is the Hadamard product of the use matrix with the pollution intensity matrix. No inversion is necessary.

Miller and Blair (2006) provide an exhaustive, if now somewhat dated, review of approaches to EEIO modeling. One of the more relevant passages is that which emphasizes the distinction among different types of EEIO structures (Miller and Blair, 2006, Section 10.2 p. 446). This passage suggests that the present work is an example of a commodity-by-industry EEIO model which reports (in this case monetary) environmental factors as "commodities" produced and consumed by industries or sectors. Section 10.6 in Miller and Blair (2006, p. 483) also shows that the present paper is, in a sense, an example of an economic-ecologic EEIO model. This approach creates an "ecosystem-submatrix", which in the context of the current analysis, reports monetary pollution damage (though this could contain emissions) in a separate matrix which is linked to the market I-O tables. Miller and Blair (2006, p. 488) also discuss linking pollution dispersion models with I-O models which is relevant here. The approach depicted therein differs from the manner in which the IAM is used in the present analysis to generate pollution damage estimates by sector and then subsequently to integrate such damages into an EEIO account.

As the present paper reports relative damages (environmental impacts) from the production of goods destined for export and avoided (local) damage from imports, the literature on multi-region I-O models used to characterize the environmental effects of trade is relevant. The European Commission's Joint Research Center (EC JRC, 2006) report provides a summary of EEIO efforts in the European Union. Among other topics, the report emphasizes the use of EEIO modeling to inform policy design and ex poste assessments.

The present paper also builds on earlier work in the field of pollution damage measurement (Mendelsohn, 1980; Muller and Mendelsohn, 2007, 2009; Muller, 2014a; 2014b), and environmental accounting (Nordhaus and Kokklenberg, 1999; Nordhaus, 2006; Abraham, 2006; Muller, Nordhaus, Mendelsohn, 2011).

Table A.1. Comparison of Results for Power Generation from Henderson, Lave, and Matthews (2006) to Utility Sector in 1999.

Sector	I	Sector	II
Total	100	Total	100
Power Generation and Supply	96.7	Utility	95.5
Rail Transport	0.8	Mining	2.4
Oil and Gas Extraction	0.7	Transport	0.1
Petroleum Refineries	0.2	Waste Mgt.	0.3
Water Transport	0.1	Manufacturing	0.1
Cement Mfg.	0.1	Construction	0.1
Stone Mining and Quarrying	0.1	Food Service, Accommodation	0.0
Support Activities for Oil And Gas Extraction	0.1	Other Services	0.0
Iron and Steel Mills	0.1	Retail Trade	0.0
Primary Smelting and Refining of Copper	0.0	Wholesale Trade	0.0
Other	3.0	Other	0.0

All results in (%) of total external cost: inputs plus value-added production.

Column (I) presents results from HLM (2006) which reported the top ten external cost generating sectors due to producing $1 million worth of electric power in the U.S. in 1997.

Column (II) presents results from the present study for utilities.

Table A.1: Real GED and VA growth, 1999 to 2011.

	Annual Growth (%)		GED as (%) of Total Economy GED	
Sector	**GED**	**VA**	**1999**	**2011**
Agriculture/Forestry	-4.074	3.247	18.60	20.31
Mining	-7.938	1.947	3.52	2.87
Utilities	-8.357	-0.360	31.69	30.82
Construction	-4.906	-2.482	6.71	7.83
Manufacturing	-7.485	1.704	16.55	15.10
Wholesale Trade	2.479	1.771	0.11	0.25
Retail Trade	-5.480	1.149	1.23	1.04
Transportation and Warehousing	-4.613	1.296	9.12	11.19
Information	-4.683	4.231	0.02	0.02
Finance and Insurance	0.452	2.528	0.00	0.00
Real Estate and Rental and Leasing	-3.311	2.344	0.02	0.03
Professional, Scientific, and Technical Services	-13.952	2.503	0.07	0.03
Management of Companies and Enterprises	61.044	0.651	0.00	0.00
Admin. Waste Mgmt. and Remediation Services	-8.839	2.820	9.53	5.48
Educational Services	-4.937	2.674	0.22	0.31
Health Care and Social Assistance	-8.658	2.715	0.11	0.08
Arts, Entertainment, and Recreation	-2.141	1.687	1.05	1.47
Accommodation and Food Services	5.169	0.980	0.78	3.09
Other Services (except Public Administration)	-18.852	-1.667	0.56	0.08
Total Economy	**-6.335**	**1.761**		

Table A.2: Input-Output Monetary Pollution Damage 1999.

NAICS	Agr./ Forestry	Mining	Utility	Constr.	Mfg.	Whlse. Trade	Retail Trade	Trans- port.	Info.	Real Est.	Finance	Prof. Serv.
Agr.	23,792	20	0	410	63,038	937	816	6	0	0	26	123
Mining	133	1,762	4,678	973	14,988	2	2	279	29	2	288	36
Utility	3,430	2,854	1,566	2,475	40,107	3,674	10,759	2,021	3,658	2,776	21,021	3,306
Constr.	54	68	132	27	701	46	130	130	163	201	1,373	179
Mfg.	957	327	218	5,514	35,993	769	861	1,365	1,212	388	756	949
Whlse. Trade	12	2	4	23	157	15	8	12	8	2	7	4
Retail Trade	1	2	5	366	86	3	23	27	2	4	36	5
Transport.	741	342	1,875	1,280	8,613	2,739	2,266	4,885	1,117	1,043	628	1,836
Info.	0	0	0	1	2	1	1	1	16	3	1	3
Real Est.	0	0	0	0	0	0	0	0	0	1	0	0
Finance	1	1	0	1	4	2	4	2	2	3	6	4
Profess. Serv.	2	1	7	13	40	19	25	8	30	38	21	48
Mgmt.	0	0	0	0	0	0	0	0	0	0	0	0
Waste	57	148	551	782	5,883	2,962	2,528	2,934	3,004	4,288	6,817	6,230
Educ.	2	0	1	0	1	5	43	0	2	0	0	1
Health	0	0	0	0	0	0	0	0	0	0	0	0
Arts/Rec.	4	0	4	9	53	39	32	15	477	74	53	143
Food/Acc.	1	0	36	19	89	27	34	83	43	133	71	202
Other Serv.	9	1	8	95	196	67	70	24	108	96	96	88
D_1	29,197	5,530	9,087	11,988	169,949	11,306	17,603	11,793	9,871	9,051	31,199	13,159
D_4	109,224	20,660	186,109	39,433	97,218	652	7,223	53,570	89	5	134	438
D_4+D_1	138,421	26,190	195,196	51,421	267,168	11,958	24,826	65,363	9,960	9,056	31,333	13,597

Table A.2: Input-Output Monetary Pollution Damage 1999.

NAICS	Mgmt.	Waste	Educ.	Health	Arts/Rec.	Food/Acc.	Other Serv.	Comm. Use	Household Use
Agr.	6	115	76	57	82	1,657	15	91,177	47,244
Mining	2	8	5	4	32	26	15	23,265	2,925
Utility	1,107	2,155	4,691	5,694	1,499	6,865	1,966	121,623	73,573
Constr.	39	11	21	65	20	105	112	3,577	47,845
Mfg.	150	530	315	2,117	137	2,088	774	55,421	211,747
Wh. Trade	1	4	2	13	1	10	4	287	11,671
Rtl. Trade	0	7	1	4	2	32	22	629	24,197
Trans.	48	925	138	918	240	447	362	30,445	34,918
Info.	1	2	0	1	0	0	0	32	9,928
Real Est.	0	0	0	0	0	0	0	2	9,053
Finance	1	1	1	5	1	1	2	43	31,290
Prof. Serv.	14	14	2	18	4	9	6	320	13,278
Mgmt.	0	0	0	0	0	0	0	0	1,959
Waste	432	3,546	348	4,055	459	916	816	46,755	16,770
Educ.	0	1	9	0	1	0	4	71	6,861
Health	0	0	0	14	0	0	0	14	13,785
Arts/Rec.	69	66	22	31	308	54	30	1,481	7,486
Food/Acc.	29	108	12	86	6	93	17	1,090	15,855
Other Serv.	60	82	12	71	15	32	125	1,256	6,296
D_1	1,959	7,575	5,652	13,154	2,807	12,337	4,270		
D_4	0	55,950	1,280	645	6,160	4,608	3,282		
D_4+D_1	1,959	63,525	6,932	13,799	8,967	16,945	7,552		

Table A.3: Input-Output Monetary Pollution Damage 2011.

NAICS	Agr.	Mining	Utility	Constr.	Mfg.	Wh. Trade	Rtl. Trade	Trans.	Info.	Real Est.	Finance	Prof. Serv.
Agr.	14,646	17	0	234	46,857	436	415	8	0	0	5	146
Mining	36	815	840	198	11,648	2	3	58	5	0	82	22
Utility	1,056	1,038	447	705	16,859	1,474	3,512	1,620	1,084	692	23,006	1,066
Constr.	65	112	175	4	408	34	69	117	75	65	3,483	22
Mfg.	818	313	194	2,559	19,223	505	594	1,742	891	191	332	829
Wh. Trade	14	3	2	28	183	24	17	19	17	2	9	9
Rtl. Trade	0	0	1	202	37	2	19	13	1	1	14	3
Trans.	460	323	584	779	6,367	2,494	2,743	4,733	836	934	393	1,455
Info.	0	0	0	0	1	1	1	0	10	2	1	2
Real Est.	0	0	0	0	0	0	0	0	0	2	0	0
Finance	1	0	0	1	2	2	4	2	2	1	5	3
Prof. Serv.	0	0	1	2	7	5	5	1	6	7	3	11
Mgmt.	0	0	0	0	1	0	0	0	0	0	0	0
Waste	16	43	188	167	1,604	1,040	768	711	564	989	4,783	2,123
Educ.	1	0	1	0	0	3	23	0	2	0	0	0
Health	0	0	0	0	0	0	0	0	0	0	0	0
Arts/Rec.	2	0	7	5	44	36	36	16	440	81	32	122
Food/Acc.	2	0	24	25	210	80	54	47	116	411	150	396
Other Serv.	0	0	0	2	7	9	6	2	4	6	9	6
D_1	17,117	2,667	2,464	4,910	103,458	6,148	8,269	9,090	4,052	3,387	32,306	6,216
D_4	78,064	11,049	118,476	30,118	58,070	966	3,996	43,030	68	7	110	101
D_4+D_1	95,182	13,716	120,940	35,029	161,528	7,114	12,265	52,120	4,120	3,393	32,416	6,317

Table A.3: Input-Output Monetary Pollution Damage 2011.

NAICS	Mgmt.	Waste	Educ.	Health	Arts/Rec.	Food/Acc.	Other Serv.	Comm. Use	Household Use.
Agr.	8	99	51	81	41	1,171	13	64,228	30,954
Mining	5	4	3	9	16	12	12	13,773	-57
Utility	1,400	511	3,801	3,294	795	2,659	1,157	66,175	54,765
Constr.	18	12	12	58	12	43	100	4,884	30,145
Mfg.	177	468	219	1,636	136	1,271	549	32,646	128,882
Wh. Trade	2	5	2	25	2	13	6	382	6,732
Rtl. Trade	0	4	1	3	3	17	14	337	11,928
Trans.	72	631	178	952	235	406	288	24,862	27,257
Info.	1	1	0	1	0	0	0	22	4,098
Real Est.	0	0	0	0	0	0	0	3	3,390
Finance	1	1	1	5	1	2	2	36	32,380
Prof. Serv.	5	3	1	6	1	2	1	68	6,250
Mgmt.	0	0	0	0	0	0	0	1	2,083
Waste	246	1,052	172	1,794	181	397	321	17,157	6,931
Educ.	0	1	12	1	6	0	9	61	5,667
Health	0	0	0	4	0	0	0	4	8,553
Arts/Rec.	88	61	24	47	346	58	25	1,467	5,954
Food/Acc.	56	178	40	306	11	86	36	2,228	15,785
Other Serv.	5	5	2	13	2	4	3	86	2,748
D_1	2,083	3,036	4,518	8,235	1,785	6,142	2,537		
D_4	2	21,053	1,210	323	5,636	11,871	298		
D_4+D_1	2,085	24,089	5,728	8,557	7,422	18,013	2,835		