

Developing a Sectoral Environmental Database for Input–Output Analysis: the Comprehensive Environmental Data Archive of the US

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ABSTRACT *This paper elucidates the data sources and data preparation procedures used in developing the sectoral environmental data of the US. The database described in this paper interlinks (1) Input–Output Table (IOT), (2) environmental emission and resources use statistics, and (3) characterization factors from Life Cycle Impact Assessment (LCIA) that quantify environmental impacts. Each of these three modules was designed to describe (1) the economic process that generates environmental interventions, (2) the quantity of the environmental intervention generated and (3) the process through which these environmental interventions realize environmental impacts, respectively. The resulting database encompasses 1344 different types of environmental interventions generated by 480 commodities of the US input–output table, linked to 86 commonly used LCIA models. This paper aims to share the experiences of and to elucidate the procedures and the data sources used for developing the sectoral environmental database in the US.*

KEY WORDS: Sectoral environmental data, input–output analysis, life cycle impact assessment

1. Introduction

Dealing with environmental issues associated with economic activities requires addressing at least three main question areas: (1) the mechanism in the economic system that generates the environmental interventions, (2) the amount of environmental interventions generated by the economic system and (3) the mechanism in the environment, with which these environmental interventions finally realize adverse environmental impacts.¹ The first question area requires a detailed insight into how an economic system is structured with respect to the technological relations between its components. The

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second question area demands extensive effort in environmental data mining. The third question area requires insights into how the biotic and abiotic systems of the Earth are configured by means of physicochemical and biological relationships. Therefore, environmental economic analyses demand knowledge not only from economics but also from diverse fields including environmental statistics, environmental sciences, toxicology, biology, chemistry, physics, and geosciences.

In this paper, the development of sectoral environmental data for use in environmental economic analysis is presented, which connects the three question areas by interlinking (1) Input–Output Table (IOT), (2) environmental emission and resources use statistics and (3) characterization factors from Life Cycle Impact Assessment (LCIA) that quantify environmental impacts. This paper aims to share the experiences of and to elucidate the procedures and the data sources used for developing the sectoral environmental database in the US.

In the next section, the content of the developed database is briefly introduced. The three following sections describe the sources and the procedures used to compile the database: i.e. the next section describes the IO data sources; the fourth section, which is the main part of the paper, deals with the environmental data; the fifth section introduces how characterization factors are derived in LCIA field. The final section concludes the paper.

2. Comprehensive Environmental Data Archive 3.0

What is generally referred to as an ‘environmental problem’ is often a combination of diverse issues, which may include natural resources use, land coverage and transformation, radiation, noise, and various emission-related issues from toxic impacts to climate change. Basically, they are all the kinds of disturbances and anthropogenic activities that adversely affect the delicate physicochemical and biological balances of the biotic and the abiotic systems of the Earth. Each of these impact areas is associated with various stressors, or environmental interventions, that become effective through a variety of complex mechanisms, which are partly known but are still largely unknown. For instance, the number of chemical substances known to humans exceeds 26 million,² but only a small fraction of them has so far revealed their amount of production, fate and the exposure mechanisms, and potential environmental implications.

Traditionally, however, analyses from the economics side tend to represent environmental impacts in an overly simple manner using a limited set of well-known pollutants, mainly CO₂, SO₂ and NO_x (see, for example, Grossman and Krueger, 1995; Suri and Chapman, 1998; Cole, 2000; and Dasgupta *et al.*, 2002). While these substances are certainly important ones, focusing only on these substances may lose insight on the possible problem shifting between different areas of environmental concerns, or safeguard subjects, especially from well-known ones to diffuse, but persistent, ones. The recent efforts in National Accounting Matrices including Environmental Accounts (NAMEA) accomplished a more comprehensive coverage of environmental interventions (de Haan and Keuning, 1996; EC, 2001), but depending on the types of application, they may still fall short of addressing the diverse environmental issues.

When the number of environmental interventions in an economic model falls in the order of several hundreds, then another problem arises: how to communicate the result? Many studies choose simply to add up hundreds of toxic substances into the total mass (see, for example, Hettige *et al.*, 1992; Mani and Wheeler, 1997; Wheeler, 2001), while

the meaningfulness of the resulting figures is questionable given the enormous differences in the fate and exposure characteristics and the toxicity of different substances.

In the domain of Life Cycle Assessment (LCA), the information of a more comprehensive set of environmental interventions is collected generally at a detailed process level (see, for example, Frischknecht *et al.*, 1996; Frischknecht, 2005). This information is then connected to LCIA models, where their behaviors in the environment and the corresponding impacts are analyzed using up-to-date knowledge from various natural sciences. Recently, increasingly more IOTs are connected to LCA studies forming a new branch of LCA approach, called Input–Output (IO) LCA. Now, national IOTs of Australia, Denmark, Germany, Japan, Netherlands, Sweden and the US are being used in connection to LCA studies (Lave *et al.*, 1995; Nansai *et al.*, 2002, 2003; Nijdam and Wilting, 2003; GDI, 2004; Weidema *et al.*, 2005; see Suh *et al.*, 2004 for a survey of existing databases).

The sectoral environmental database of the US, named ‘Comprehensive Environmental Data Archive (CEDA)’ 3.0, follows the tradition of IO-LCA but with more ambitious objectives: CEDA 3.0 covers a total of 1344 environmental interventions that are related to the 480 commodities distinguished in the US and that are linked to 86 widely used environmental models. The environmental interventions covered range from 1-(3-Chloroallyl)-3,5,7-Triaza-1-Azoniaadamantane Chloride to Ziram with the base-year of 1998.³ The database is derived from various environmental databases, including the Toxics Releases Inventory (TRI), National Toxics Inventory (NTI), National Emissions Trend (NET) databases, greenhouse gas emissions and sinks data, agricultural chemical and fertilizer use data, mineral and fossil fuel resource use database, energy consumption data, and land use data. The interventions covered include resource use (six items), land use (one item), and environmental emissions to air (551 items), to freshwater (331 items), to industrial soil (236 items), and to agricultural soil (219 items) and relate to over 480 commodities produced in the US. With the 1344 environmental interventions, CEDA 3.0 covers the key driving causes of major environmental impacts such as global warming, ozone layer depletion, various toxic impacts to humans and ecosystems, acidification, eutrophication, land use and resource depletion.

The data on environmental interventions that are compiled and related to the US input–output sectors are then connected to characterization factors of LCIA, allowing users to aggregate environmental interventions into environmental impact scores. The selected impact assessment methods include Global Warming Potentials (GWPs), Ozone Depleting Potentials (ODPs), CML2002 methods, Environmental Priority Strategies (EPS) method, Swiss Eco-Point method and Eco-Indicator 99 methods, which cover diverse environmental issues such as natural resources depletion and various toxic impacts to humans and ecosystems. A description of environmental LCIA models, including those selected for inclusion in CEDA 3.0, can be found in Guinée *et al.* (2002).

The resulting database is applicable to various environmental economic analyses including policy modeling, Material Flow Analysis (MFA), Substance Flow Analysis (SFA), LCA, analyses of consumption and its environmental impacts, and alternative material selection in environmental design.

3. Input–Output Data

CEDA 3.0 uses the US 1998 annual input–output tables (BEA, 2002) and a calculation procedure to derive a commodity \times commodity table that follows the standard US

make-and-use framework provided in BEA (1995a, b). The 1998 annual input–output table, which distinguishes around 500 sectors, is appended with capital flows information. The most recent capital flow matrix available then was for the year 1992 (BEA, 1995c). The amount of capital goods used by each sector has been inflated or deflated depending on price change information and gross output differences between 1992 and 1998 for the sector in question. In the 1992 benchmark survey by BEA, uses of 163 capital goods by 64 industries were compiled on the basis of SIC code. These have been reassigned to the relevant IO categories for inclusion in the use matrix (see, for example, Lenzen, 2001).⁴ The resulting make-and-use matrices are then used to construct commodity \times commodity technology coefficient matrices following the standard industry-technology models.

4. Compilation of Sectoral Environmental Data

Compilation of environmental data is not a straightforward process of simply collecting data, but involves various assumptions and modeling efforts to harmonize and assemble fragmented, and often incompatible, information. In this section, the data sources and the data preparation procedures used in developing the CEDA 3.0 database are described.

4.1. Greenhouse Gas Emission

Total US greenhouse gas (GHG) emissions, including carbon dioxide (CO₂) emissions, are fairly well established. Apart from the CO₂ emission data for the electric utility sector compiled by the Energy Information Administration (EIA) and Environmental Protection Agency (EPA), however, data at the level of individual sectors are not readily found. Consequently, the rest of the estimation procedure for combustion-oriented CO₂ emissions focuses on sectors other than the electric utility sector.

With regard to transportation, there are two categories of CO₂ emissions to be distinguished: those of household transportation and industrial transportation. In CEDA it is assumed that the use of all trucks, buses, aircraft, boats and vessels and locomotives are part of industrial activities. CO₂ emissions from international bunker fuel combustion, construction equipment and agricultural vehicles are also assigned to industrial use. CO₂ emissions from all other activities, mainly driving passenger cars, are assumed to be household activities.⁵

CO₂ emissions reported under the headings ‘industry’ and ‘commercial’ have been assigned to individual IO industries based on the transaction records for the fuel types in question and the data on combustion-oriented CO₂ emissions by fuel type compiled by EPA (EPA, 2002a). Non-combustion-oriented CO₂ emissions have been assigned based on the source process cited by EPA (2002a). The remaining emission sources could be allocated directly to the appropriate IO industrial sectors. The findings are reported in Table 1.

4.1.1. Methane

In 1998, emissions of methane (CH₄) accounted for 9.3% of total industrial and households GHG emissions of the US (627.1 Tg CO₂-equivalents). Besides enteric fermentation (particularly by ruminants), industrial processes such as landfills, natural gas systems and coal mining are the predominant sources, and these ‘area sources’ can be readily assigned to a relevant IO classification.

Table 1. Direct US industrial carbon dioxide emissions, by sector

	Aggregated sector	Sources	Emission (Tg CO ₂)	Sector's share
Combustion-oriented	Electric utility	Electric utility	2160.3	46%
		Industry	137.8	21%
	(based on fuel consumption)	Natural gas	484.1	
		Petroleum	194.2	
		Lubricant oil	12.7	
		Other petroleum	171.3	
		Transportation	Light duty trucks	356.4
	Transportation	Other trucks	257.9	
		Buses	12.4	
		Aircraft	183.0	
		Boats and vessels	47.8	
		Locomotives	33.8	
		Construction and agricultural equipment	93.0	
		International bunker fuel	112.9	
Commercial		Coal	8.7	5%
(based on fuel consumption)	Natural gas	163.5		
	Petroleum	47.2		
Non-combustion-oriented	Industrial processes	Iron and steel	67.4	4%
		Cement manufacturing	39.2	
		Waste combustion	20.3	
		Ammonia manufacturing	20.1	
		Limestone and dolomite	21.9	
		Natural gas flaring	6.3	
		Soda ash manufacturing	5.8	
		Titanium dioxide	4.3	
		Ferrous alloys	1.8	
		CO ₂ consumption	1.4	
		Total		

Note: Based on EIA (2002), EPA (2002a) and own calculations.

Given the CH₄ emission factors for residential and commercial coal combustion (300 and 10, respectively) and respective consumption of the two sectors in 1998 (13 Tbtu and 92 Tbtu), based on coal consumption, only 19% of CH₄ emissions from ‘stationary’ sources have been assigned to intermediate industries (EIA, 2002; EPA, 2002a). According to EPA (2002a), 42% of CH₄ emissions from mobile sources were due to passenger cars. Assuming other means of transportation can be assigned to intermediate industries, 58% of ‘mobile’ CH₄ emissions can then be assigned on the basis of transportation service transaction records, and this has been done in CEDA (see Table 2).

4.1.2. Nitrous Oxide Emissions

Because of their very minor contribution to overall GHG emissions, only two N₂O sources have been deemed significant: ‘agricultural soil management’ and ‘mobile sources’, contributing 1.0 Tg and 0.2 Tg of CO₂-equivalent GHG emissions (963 Gg and 191 Gg as N₂O), respectively. Following the same line of reasoning as for CH₄, 46% of N₂O emissions from mobile sources have been assigned to intermediate industries on the basis of transportation service utilization.

Table 2. US industrial methane emissions, based on direct emission

Source	Emission (Gg CH ₄)	Share (%)
Landfills	9571	39.91
Natural gas systems	5820	24.27
Coal mining	3235	13.49
Manure management:		
Dairy cattle	624	2.60
Swine	864	3.60
Beef cattle	161	0.67
Sheep	2	0.01
Goats	1	0.00
Poultry	130	0.54
Horses	29	0.12
Wastewater treatment	1326	5.53
Petroleum systems	1114	4.64
Stationary sources	334	1.39
Rice cultivation	376	1.57
Mobile sources	123	0.51
Petrochemical production	78	0.33
Agricultural residue burning	37	0.15
Others	153	0.66
Total	23984	100

Note: Based on EPA (2002a).

4.1.3. Other Greenhouse Gas Emissions

CEDA 3.0 also covers the following greenhouse gases: Trichloromethane, Sulfur Hexafluoride, Tetrachloromethane, Perfluorobutane, Perfluorocyclobutane, Perfluoroethane, Perfluorohexane, Perfluoromethane, Perfluoropentane, Perfluoropropane, Methylbromide, Methyl Cyclohexane, Halon-1211, Halon-1301, seven different HCFCs, 13 different HFCs, six different CFCs, and Dichloromethane. However, their contribution is generally insignificant for most industries.

4.2. Criteria Pollutants

The term 'criteria pollutants' in the US refers to six air pollutants: carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO₂), particulate matter (PM),⁶ ozone (O₃) and lead (Pb). Four of these, CO, NO_x, SO₂ and PM, have been compiled and maintained by the US National Emissions Trend (NET) database, which is now being absorbed into the National Emissions Inventory (NEI) database together with the National Toxics Inventory (NTI) database for Hazardous Air Pollutants (HAPs) (EPA 2002c, d). The NET database covers both point sources and non-point sources, including area sources and mobile sources. The point source emissions compiled in the NET database provide detailed information on emission sources at the facility level and also indicates the SIC code of the facility. The point source section of the database can therefore be readily assigned to the appropriate industry on the basis of SIC codes. In CEDA 3.0, the most detailed SIC code set has been used to assign SIC-based information without losing resolution. The NET database for point source criteria pollutant emissions covers a total of 1037 SIC

industries, and these emissions have been converted into 500 BEA industry codes, based primarily on the standard comparison between SIC and BEA codes prepared by BEA. In cases where an SIC code can be subsumed under more than one BEA heading, additional data sources such as main source facility type or total amount of industry output have been employed to split the emission figure over multiple BEA sectors.

Non-point sources have no SIC code, but as these are described in detail they can readily be tied to an IO industry classification code. For non-point sources, including both mobile and area sources, NET provides a more aggregated classification of emission sources (less than 200 source-types). Therefore, emissions from non-point sources have been converted to the BEA industry classification based on several assumptions. For instance, CO emissions from ‘agricultural fires’ have been assigned to 16 agricultural industries in the BEA classification based on their share of total output, and NO_x emissions from ‘on-road vehicles’ have been assigned to 500 BEA industries based on the rate of on-road vehicle utilization by each industry, assuming that use of truck and bus services represents industrial use of on-road vehicles. Non-anthropogenic sources such as forest wildfires have not been assigned to intermediate industries.

4.3. Volatile Organic Compounds (VOC) and Ammonia

These two pollutants are also covered by the NET database and the procedure and data sources employed in CEDA to compile these pollutants are similar to those used for the criteria pollutants.

4.4. Toxic Pollutants

The toxic pollutants part of the database is the most challenging, even in the US, which probably has the most advanced monitoring and reporting system for toxic chemicals in the world. In the US, toxic emissions are dealt with under a number of different initiatives, including the Toxics Releases Inventory (TRI), National Toxics Inventory (NTI) and National Center for Food and Agricultural Policy (NCFAP) database (EPA 2002b, c, d, NCFAP 2000). These databases comprise extensive arrays of toxic chemicals: 535 in TRI98, 188 in NTI and 235 in NCFAP. Nonetheless, certain important chemicals could be missing, although the list is based on up-to-date knowledge of toxic chemicals. However, identification and quantification of other toxic chemical releases than those covered by these databases was not considered a priority in CEDA 3.0, and, thus, only those chemicals listed in the cited databases have been included.⁷

Table 3 summarizes the scope of the three databases in terms of emission source types, industries, environmental media and emissions from facilities below the threshold limit. A glance at Table 3 indicates that none of the databases cover emissions to water and land (other than pesticides) by mobile and area sources, NTI covering only Hazardous Air Pollutants (HAPs) and TRI mainly point sources only. While toxic pollutant emissions to environmental media other than air by mobile sources are not considered to be significant, those from area sources, such as leachate emissions from landfills, could be considerable. These gaps have, meanwhile, been fairly well filled; however, following a recent extension of the TRI databases, especially for Mining (SIC 1021 to SIC 1474), Logistic services (SIC 4212 to SIC 4581), Sewerage and refuse systems (SIC 4952 and SIC 4953) and Solid waste management (SIC 9511). In addition to these sectors, since 1998 most major

Table 3. Coverage of toxic emission databases

Scope of database		TRI	NTI	NCFAP
Source type	Area	–	Good	Good
	Mobile	–	Good	–
	Point	Good	Good	–
Industry	Agricultural and mining	Moderate*	Poor	Good
	Manufacturing	Good	Good	–
	Services	Moderate*	Good	–
Substances	Air	Good	Moderate	–
	Water	Good	–	–
	Soil	Good	–	Moderate**
Coverage within industries	Reports from larger facilities only	Moderate	Good	–
	Estimation for facilities below thresholds	–	Good	–

*Since 1998 some of these activities have been covered by TRI.

**Whether the pesticide applied is an emission to air, water or soil depends very much on the properties of the applied chemical, climate conditions, etc. However, here the arguments are postponed to the stage of impact assessment method specification, and the emission itself is regarded as an emission to soil.

chemical-handling sectors have also been included in the TRI database, and industry coverage by this database therefore seems reasonably complete, although obviously not 100%. This has indeed been confirmed, for air emissions at least (see Figure 1). According to the NTI database, a total of 3,669,196 tons of HAPs was emitted in the US in 1996, with Manufacturing industries (SIC 20 – SIC 39) and Electricity, sewerage and refuse systems (SIC 49) contributing around 97%, emitting 2,202,304 tons and 1,338,170 tons, respectively. Thus, the major industries generating all but 2% of HAP emissions are within the scope of the extended TRI database.

However, emission reports for the TRI 98 database are collected only from those facilities employing 10 or more full-time equivalent employees or manufacturing or processing over 25,000 pounds or otherwise using over 10,000 pounds of any listed chemical during the reporting year. Although the emission from each individual facility not meeting these conditions may well be small, together they may be quite substantial. Therefore, it is important to quantify the possible magnitude of truncation in TRI database due to the threshold conditions.

The completeness of the TRI database has been examined using the NTI database and establishment size distribution data compiled by the Census Bureau (2001). The NTI database estimates HAP emissions using reports as well as emission factors and activity rates, regardless of the size of facilities. A comparison between TRI and NTI for overlapping chemicals can therefore provide an indication of the truncation of TRI of facilities below the threshold. Unfortunately, however, the NTI database for 1998 was not compiled and the most recent NTI data available then was the one for 1996, and, therefore, the comparison could have been carried out only between TRI 98 and NTI for 1996 (see Figure 2). The data points in Figure 2 show the amount of releases of overlapping chemicals reported in TRI 98 and the NTI for 1996 whose yearly releases are more than 1 ton. The thin, main diagonal line indicates the case where TRI and NTI report the same value. The thick line above is the regression result based on the data from TRI and NTI. Even if the two years of

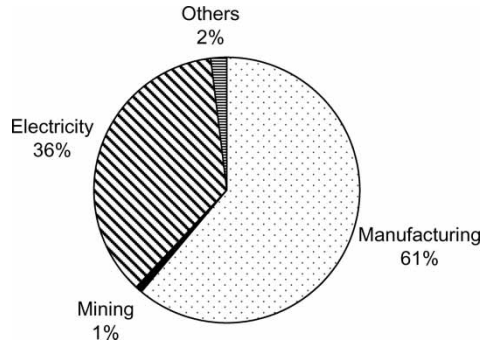


Figure 1. Contribution by industries to NTI database by mass

temporal difference are taken into account, this comparison suggests that there might be significant systematic truncations in TRI showing only 17.2% of HAP emissions, on average, as compared to NTI. This strongly suggests that using only TRI may significantly underestimate the potential impacts of toxic releases.⁸

One explanation for such large differences between the two databases might lie in the size distribution of establishments. Given the wide range of processes involved, each industry has different establishment size distribution characteristics. For instance, the North American Industry Classification System (NAICS) 323, Printing and related

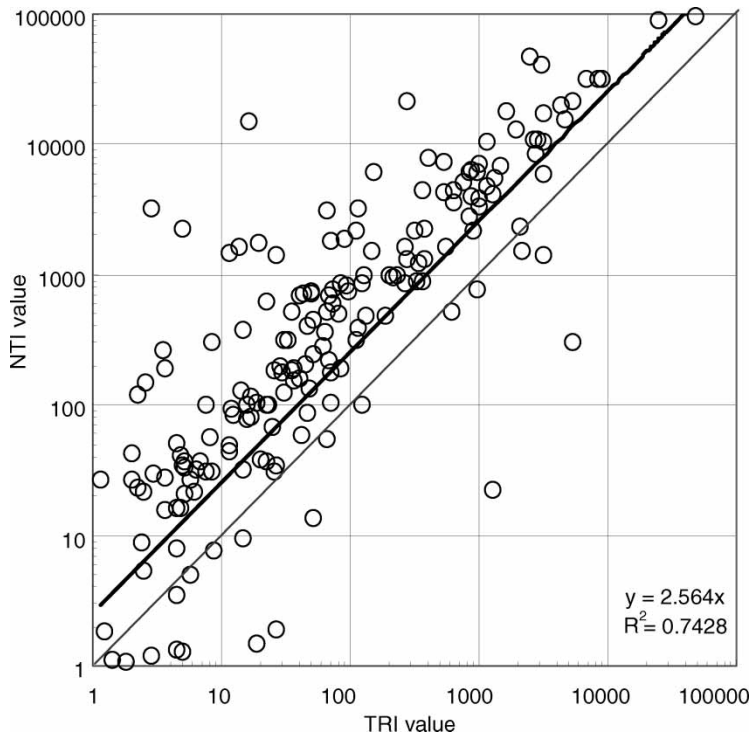


Figure 2. The relationship between reported emissions by mass in TRI and NTI

support activities is dominated by establishments with less than 10 employees, which account for 66% of the total of 42,863 establishments, while the share of these smaller establishments in the Paper manufacturing sector (NAICS 322) is only 20% of the total of 5868 (Census Bureau, 2001). The larger the number of smaller establishments in an industry, the less complete the TRI data for that sector will probably be. Besides, following from the nature of the threshold, this is also due to emission standards generally being less strict for small-sized establishments and again, although such establishments may generate smaller volumes of toxic emissions individually, their sum total may be substantial.⁹

The regression study was further extended to the level of individual industries in order to reflect the differences in establishment size distribution. The TRI values for each sector represent, on average, 4.4% to 29.4% of the HAPs reported by NTI, depending on the sector involved.¹⁰ These results do not support the argument that TRI can still indicate the relative magnitude of toxic impacts even though their absolute values are misleading due to homogeneous truncation. Due to the difference in the base years between the TRI and the NTI databases used for the comparison, the regression results are considered to be highly uncertain and, therefore, CEDA 3.0 contains not only the datasets with the estimation procedure but also the original data in these reports.

In compiling CEDA 3.0, the relatively complete data sources such as NTI for HAPs have been utilized as far as available. Otherwise, sectoral toxic emissions have been estimated based on TRI and the relationships between TRI and NTI values derived for each individual sector. In cases where no such sectoral relationships could be established, owing either to sample size or to poor regression results, more general relationships between TRI and NTI have been used instead.

For mobile and area sources, direct use has been made of the NTI database, with no further adjustments as it is considered to cover most major emissions. Besides point source emissions, the NTI database also includes emissions from natural processes and post-production stages, including wildfire, household product usage, etc, and these emissions have been excluded from subsequent assignment to individual industries.

For pesticide emissions, direct use has been made of the NCFAP and other databases (Aspelin and Grube, 1999; NCFAP, 2000). This database compiles and maintains volume records of 235 pesticides applied to 88 types of crop. On the assumption that the amount of pesticide applied equals emission, pesticide emission data have been assigned directly to a BEA industry code based on crop type.

In CEDA 3.0, users can choose between the two sets of environmental data: one based on the data without using the estimation procedure that was employed to cover the missing emissions and the other with such a procedure.

4.5. Land Use

In this part of the CEDA database, only uses of land by major land-covering activities are accounted for (in square meters).¹¹ In addition, mere occupation of land is all that is considered, with differences in neither land-use intensity nor land transformation being accounted for. Figure 3 shows the major forms of land use in the US. The Special uses cited in Figure 3 include parks, wilderness, wildlife and related uses, transportation and national defense areas, while Others covers deserts, wetlands and barren land. Land uses that can be related to industrial production are croplands, grassland, part of Special

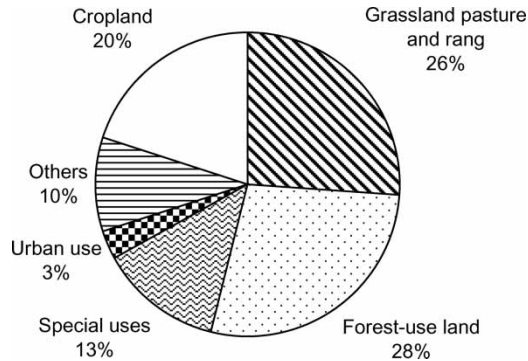


Figure 3. Major uses of land in the US (USDA, 2002) (Total area of land in used in 1997: 2.3 billion acres.)

uses (recreation, transportation and defense) and part of urban use (for industrial installations). Urban use here includes industrial complexes and service areas other than agricultural uses, as well as urban residential areas. Most US industrial activities take place in urban areas, accounting for around 3% of land use in this category. The average land coverage of each individual BEA sector is thus less than 0.006% at most, and these figures have therefore not been included in the CEDA database.¹²

Among Special uses, natural parks are the largest category; however, these are not considered to be an environmental intervention and have therefore not been included in the CEDA database either. Several land use activities need to be allocated to appropriate industries. As both industrial and household activities contribute to land use for transportation, the share of the former was estimated based on the CO₂ emissions of passenger cars and other road vehicles such as trucks and buses. According to EPA (2002a) passenger cars are responsible for 36% of total CO₂ emissions by road vehicles. Thus, only 64% of total land use for transportation has been allocated to the transportation sector, based on respective total production values.¹³ Grassland pasture and range has been allocated to livestock industries, again based on total production value. The remaining industrial uses of land have all been allocated directly to BEA codes (see Table 4).

4.6. Nitrification

Nitrification is due principally to emissions of nitrogenous and phosphorus compounds to air, freshwater and soil. The main emission sources include combustion gases (for NO_x to air) and application of fertilizer and manure (for emissions of nitrogenous and phosphorus compounds to freshwater). NO_x and NH₃ emissions from these sources are fully accounted for in the NET database. Although some nitrogenous emissions from manure application may subsequently undergo a series of biological processes known as nitrification and denitrification, forming nitrite (NO₂⁻), nitrate (NO₃⁻) and nitrogen gas (N₂), most are in the form of NH₃ or NH₄⁺, depending on the ambient pH (or in the form of organic nitrogen), at the time of initial manure application to agricultural soils. For nitrogenous emissions, direct use has therefore been made of the NH₃ inventory of the NET database

Table 4. Industrial uses of land in the US

	Detailed use	Area (million square meter)	Share of total industrial use (%)
Cropland	Soybeans	408777	10.68
	Corn for grain	397729	10.39
	All wheat	303821	7.94
	Cotton	75495	1.97
	Sorghum for grain	47875	1.25
	Other crops	40509	1.06
	Corn silage	34985	0.91
	Barley	27620	0.72
	Rice	20255	0.53
	Sunflower	20255	0.53
	Oats	14731	0.38
	Dry edible beans	11048	0.29
	Non-citrus fruits	11048	0.29
	Fresh market vegetables	11048	0.29
	Sugarbeets	9207	0.24
	Processing vegetables	9207	0.24
	Peanuts for nuts	7365	0.19
	Potatoes	7365	0.19
	Canola	5524	0.14
	Sugarcane	5524	0.14
	Citrus fruits	5524	0.14
	Tobacco	3683	0.10
	Millet	3683	0.10
Tree nuts	3683	0.10	
Rye	1841	0.05	
Sorghum silage	1841	0.05	
Grassland pasture and range	Grassland pasture and range	2339108	61.09
Special uses	Transportation	101173	2.64
	National defense	60704	1.59

Emissions of phosphorus (P) compounds are not readily available in any of the major statistical archives and these have therefore been estimated in terms of phosphorus equivalents, using several databases. The CEDA inventory covers phosphorus emissions due to manure application and phosphorus run-off from phosphate fertilizer application (see Table 5).

NRCS (2000) provides data on the average mass excreted daily by each type of livestock, its P content and the average run-off ratio. These data have been employed together with the NASS (2003) statistics on US 1998 livestock numbers to estimate annual P emissions to freshwater due to manure application (see Table 6). Over half the phosphate fertilizer applied in the US is in the form of ammonium phosphate (NH_4HPO_4), containing 88–90% of active ingredient. The phosphorus content of ammonium phosphate fertilizer is thus around 22% by mass. NASS (1998, 1999, 2000, 2003) provides data on the amount of phosphate fertilizer applied to each type of crop (including fruits, vegetables and nuts). By applying the average phosphorus run-off rate to soil estimated by NRCS (2000), the level of phosphorus loss to soil was then estimated for use in CEDA 3.0.

Table 5. Major phosphorus emissions from livestock

	Number (thousand)	g of P excreted/ yr per head	Estimated loss (%)	Annual emission (kg/yr)
Beef cattle	33885	18.23	15	92648.88
Dairy cattle	9199	9.9426	15	13719.3
Chicken	425045	53.0272	15	3380842
Swine	62206	26.5136	15	247395.8
Turkey	5549	46.3988	15	38618.66
Total				3773225

Note: Own calculation based on NRCS (2000) and NASS (2003).

4.7. Resource Depletion

The only resource types considered in CEDA are fossil fuels, iron ore, copper ore, and sand and gravel. Given the homogeneity assumption and the level of aggregation of the current IO table, there was felt to be little point to compile data on other mineral resources. For instance, any purchase from the ‘inorganic chemicals’ sector will be regarded in an IO framework as a blend of all kinds of mineral resources from gold to silicon, regardless of the specific material actually purchased. Compared with other industries using natural resources, however, the energy sector and the iron and steel industry are reasonably homogeneous. Figures for natural gas extraction have been taken from EIA (2003a), data on crude oil consumption from EIA (2000) and data on coal from EIA (2003b). Statistics for iron ore, copper ore and sand and gravel extraction are from USGS (2000).

4.8. Derivation of Environmental Matrix

Since a commodity × commodity matrix is utilized for the input–output part, the dimension of the environmental intervention matrix should likewise be intervention × commodity. For instance, the equation

$$\mathbf{m} = \mathbf{B}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{1}$$

where \mathbf{B}' is an environmental intervention × industry matrix representing the environmental interventions caused by the production of 1 dollar’s worth of industry output, \mathbf{A} is a commodity × commodity input–output technology coefficient matrix, \mathbf{y} a final demand vector, and \mathbf{m} is the total economy-wide environmental intervention calculated by this equation, is, although encountered in some of the literature, not congruent. In CEDA, the standards make-and-use framework is used to derive the intervention × commodity matrix.

Information on environmental interventions is compiled mainly on an industry rather than commodity basis. The environmental intervention matrix must therefore be derived from \mathbf{B}' , by assigning the aggregate environmental intervention of each industry to its secondary products and scrap as well as its primary product. Assuming that the sum total of environmental interventions by a given industry is assigned proportionally to its primary and secondary products based on their economic value, the average environmental intervention due to a dollar’s worth of commodity can then be calculated on the basis of market

Table 6. Phosphorus emissions due to fertilizer application

	Phosphate fertilizer applied (million pounds)	P content (kg)	P run-off (kg)	Share of total (%)
Corn	3236.50	3.23E+08	4.85E+07	51.07
Wheat	1326.40	1.32E+08	1.99E+07	20.93
Soybean	763.60	7.63E+07	1.14E+07	12.05
Cotton	378.20	3.78E+07	5.67E+06	5.97
Grapes	306.04	3.06E+07	4.59E+06	4.83
Sorghum	54.50	5.44E+06	8.17E+05	0.86
Oranges	35.94	3.59E+06	5.38E+05	0.57
Lettuce	35.41	3.54E+06	5.31E+05	0.56
Tomatoes	35.25	3.52E+06	5.28E+05	0.56
Melons	25.72	2.57E+06	3.85E+05	0.41
Onions	14.91	1.49E+06	2.23E+05	0.24
Corn	13.06	1.30E+06	1.96E+05	0.21
Carrots	12.38	1.24E+06	1.85E+05	0.20
Almonds	11.77	1.18E+06	1.76E+05	0.19
Beans, Samp, Proc.	8.93	8.92E+05	1.34E+05	0.14
Cabbage	8.91	8.90E+05	1.33E+05	0.14
Peas	8.84	8.82E+05	1.32E+05	0.14
Broccoli	8.13	8.12E+05	1.22E+05	0.13
Beans, Samp, Fresh	6.91	6.90E+05	1.03E+05	0.11
Celery	4.71	4.71E+05	7.06E+04	0.07
Peppers	4.65	4.65E+05	6.97E+04	0.07
Grapefruit	4.57	4.56E+05	6.85E+04	0.07
Apples	3.88	3.88E+05	5.82E+04	0.06
Cucumbers	3.17	3.17E+05	4.75E+04	0.05
Spinach	3.00	3.00E+05	4.50E+04	0.05
Strawberries	3.00	2.99E+05	4.49E+04	0.05

Note: Own calculation based on NASS (1998, 1999, 2000, 2003) and NRCS (2000).

share as

$$\mathbf{B} = \mathbf{B}'\mathbf{D} \quad (2)$$

where \mathbf{B} is an environmental intervention \times commodity matrix and \mathbf{D} is a market share matrix derived from make-and-use matrices. This method, which corresponds to the industry-technology assumption, was used for deriving the environmental intervention matrix in CEDA 3.0.

Alternatively, one can assume that each commodity generates its own characteristic environmental interventions, irrespective of the industry producing it. Under this assumption, commonly called the commodity-technology assumption, the total environmental intervention of a primary product of a given industry is calculated by subtracting the total environmental intervention due to secondary products, indexed to industries producing these secondary products as primary products. In LCA this method is referred to as the 'avoided impact' allocation method or 'system expansion' method and corresponds to the commodity-technology assumption in the make and use framework (for details, see, for example, Kagawa and Suh, 2005). The resulting environmental intervention matrix

generally contains numerous small negative values, which requires careful interpretation. In the public version of CEDA 3.0, only the environmental matrix derived from the industry-technology assumption is included, while the one from the commodity-technology assumption can be supplied upon request.

5. Characterization Factors of LCIA

Once the amount of total environmental interventions directly and indirectly generated is calculated using the input–output table and the environmental intervention data delineated in the two previous sections, quantification of environmental impacts follows. It is notable that LCIA is not the only approach to quantify environmental impacts, but there are a number of widely used approaches including Environmental Impact Assessment (EIA), Risk Analysis (RA) in addition to LCIA. Each of the approaches has different objectives and scope: EIA is a highly institutionalized procedure that is used to measure possible environmental implications of certain decision prior to the decision actually being enforced. An example is an EIA for a new, residential area development of a certain location, where the possible hazards of such development to its soundings are addressed. EIA is used more as a ‘pass-fail’ criteria, its main focus being on a local environment. The target problem of RA is more specific than EIA, and it generally deals with the fate, transportation and exposure of a specific, and generally toxic, substance in and around a contaminated site (EPA, 1991). In contrast to EIA, a RA study generally, though not necessarily, takes place after certain contamination is noticed. As compared to these approaches, the scope of an LCA is much broader, covering the major environmental concerns of the modern society. As a modeling framework, LCA is more time- and space-generic, meaning that it generally integrates the environmental impacts that take place over time and space in quantifying the potential environmental impacts of a product life-cycle.¹⁴ Many characterization factors are derived at a national or at a continental scale rather than at the level of a specific contaminated site or of an emission source. The derived characterization factors are, therefore, more suitable for the analyses at a national or at a continental level, which is more in line with the geographical scale of IOA. The rest of this section intends to provide a general introduction to how characterization factors in LCIA are derived. Detailed discussion on LCIA models, including these included in CEDA 3.0, can be found in Guinée *et al.* (2002).

LCA consists of four major steps: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 1998). In the goal and scope definition phase, the objective of the study, its intended application, the required data quality, system boundary and so on are set. In the Life Cycle Inventory (LCI) analysis phase, data on environmental interventions are collected or calculated, on-site from an appropriate industry or using LCA databases, respectively. In the impact assessment phase, the environmental impacts of the product or service are assessed by multiplying LCI results by relevant characterization factors quantifying the relative contribution of each environmental intervention to a particular environmental impact category such as global warming or ozone layer depletion (Guinée *et al.*, 2002). To arrive at more aggregate indicators, this ‘characterization’ step may be followed by a number of additional steps, including normalization, grouping and weighting. These post-characterization steps are not incorporated in CEDA 3.0 but may be pursued by individual users.

The characterization step is briefly described below. The concept of characterization, as is currently used in LCA, has been developed independently in several scientific communities. In LCA, Global Warming Potentials (GWPs) and Ozone Depleting Potentials (ODPs) are among the most familiar characterization indicators currently employed. Once generated, any environmental intervention goes through a series of physical and chemical processes before eventually culminating an environmental problem. For instance, SO_2 emissions combine with water to form H_2SO_4 , which may be ionized to 2H^+ and SO_4^{2-} . As precipitation transfers these hydrogen ions to the soil system and lowers soil pH, the resultant acidification process may impact on vegetation and forestry. Together, these successive processes are referred to as an environmental mechanism (see Figure 4). Some environmental mechanisms are fairly simple, but most are complex and involve a multitude of physical and chemical transformations and fate and exposure routes. In an LCIA, a category indicator is chosen along with the environmental mechanism in such a way that the indicator reflects an important causal and quantitative relationship with the category endpoint. For instance, the total number of hydrogen ions generated in the process of acidification may provide a good category indicator. Using selected category indicators, each environmental intervention can be represented in terms of its equivalence to a reference intervention in the impact category in question. In the case of global warming, for instance, the radiative force of each greenhouse gas is chosen as a category indicator (termed Global Warming Potential) and CO_2 as the reference intervention for 1 GWP.

Characterization factors are simply a set of factors for converting environmental intervention results into the equivalent terms of a reference intervention. Depending on the characterization model used, the time horizon considered and the physical location of the category indicator, however, a number of different approaches are available to this end. Notably, the models used in LCIA can be categorized by the location where the category indicator is extracted along with the environmental mechanism. Early developments

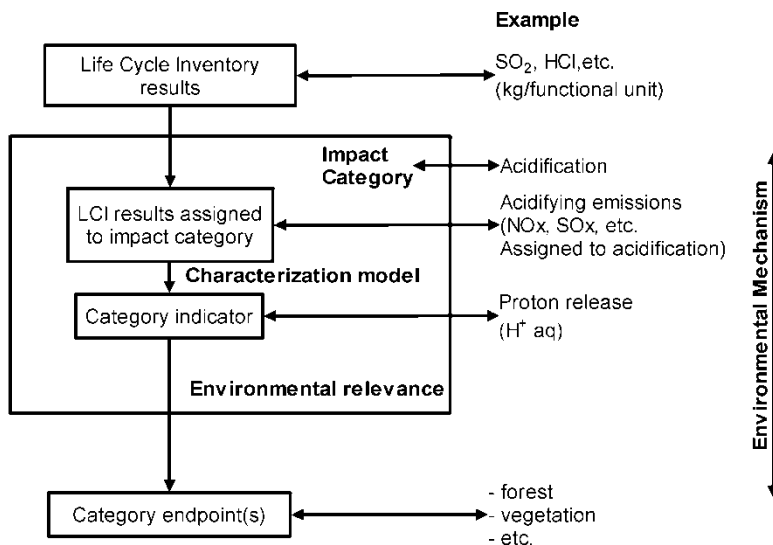


Figure 4. Concept of category indicators (ISO, 1999)

in LCIA generally preferred to choose the category indicator at an early stage of environmental mechanisms, such as the increased radiative force in global warming mechanism and proton release in acidification mechanism (see Heijungs *et al.*, 1992a, b). Recently, LCIA models started to incorporate the category indicators near the category endpoints (Hofstetter, 1998; Itsubo *et al.*, 2004). Progress is being made in these two schools of LCIA, namely mid-point and end-point modeling, and, to a certain extent, a combination of these two models is being implemented (see, for example, Heijungs *et al.*, 2003; Jolliet *et al.*, 2003a).¹⁵

The 86 methods included in CEDA 3.0 cover and embrace the characterization factor sets that are most widely referenced, including those derived from the mid-point and the end-point models (Goedkoop and Spriensma, 1999; Guinée *et al.*, 2002). These factors are linked internally to all other interventions to avoid errors in linking interventions with appropriate factors. Nevertheless, individual users can choose other LCIA models than those used in the database by exporting the inventory results and linking them to the preferred characterization factors. For the list of LCIA models used in the database, see Suh (2004).

6. Discussion and Future Outlook

This paper describes the development of sectoral environmental data in the US. Compilation of sectoral environmental databases involves various modeling efforts to harmonize and to assemble fragment, and often incompatible, information. For instance, in developing CEDA 3.0, a comparison between TRI and NTI databases indicated that the missing emissions due to the threshold condition in TRI may be significant, for which a regression analysis is carried out to estimate the missing portion. In this paper, the data sources and the data preparation procedures used in developing CEDA 3.0 database are described in detail.

Data works generally require a significant amount of time and labor, while the result of this kind can never be complete. Nevertheless, reliable and up-to-date primary data are, needless to say, a requirement for sound modeling practices. In this regard, there are yet many obstacles to be overcome to enable a more reliable sectoral environmental database.

First, economic statistics and environmental statistics need coordination. As the generation of environmental interventions are not separable from the embedding economic activities, the two need to share at least a common sector classification. Even in the US, where environmental statistics are well-established, the two use different sector classifications, demanding a laborious transformation procedure. As both economic and environmental statistics are based on rather institutionalized procedures, once established, they tend to be locked-in by the rigidity of the procedure and by the cost of nation-wide reform. This draws attention to the need of coordination between economic and environmental statistics in advance, especially for the countries planning to reform or to establish their environmental statistics. The Systems of Environmental and Economic Accounts (SEEA) and NAMEA frameworks (de Haan and Keuning, 1996; EC, 2001; UN, 2003) certainly provide a starting point, while the efforts to fill-in such frameworks will need to be followed in individual countries.

Second, environmental information needs to be improved in most countries. The CEDA 3.0 database is based on US environmental statistics, which cover an extensive list of

environmental interventions. Such a database is, unfortunately, unavailable in most countries. There are a number of international initiatives that are underway to improve environmental statistics including Pollutant Release and Transfer Registers (PRTR).¹⁶ These initiatives are expected to contribute to improving the coverage and reliability of environmental statistics, while its success is again dependent upon the efforts to be exerted by the individual countries in implementing these frameworks.

The database presented in this paper has been incorporated in commercial and non-commercial LCA software packages and has been successfully utilized in Integrated Product Policy (IPP) studies notably by the European Commission (EC) and the Danish Environmental Protection Agency (Goedkoop, 2004; Tukker *et al.*, 2005; Weidema *et al.*, 2005). Nevertheless, the database is subject to further updates. First, quantitative uncertainty information needs to be attached to the database. Deriving and assigning quantitative uncertainty information to individual data cells has been a challenge, as the database contains half a million data entries. If the background data used to derive them are included, there are over one million cells that need to be assigned uncertainty figures. Second, environmental impacts associated with imports, which are currently assumed to be the same as those of domestically produced products, need to be better identified. Although the amount of imports in the US is relatively marginal in monetary terms, their environmental implication may not be as marginal as their monetary values suggest. Third, a number of key sectors that contribute a significant part of the overall environmental impacts need further disaggregation as well. The database is planned to be regularly updated using up-to-date data sources as well as LCIA models.

Notes

¹Given the mutual interconnectedness between the two systems, it is not only that the economy influences the environment but also that the aggravated environment adversely affects the economy. The latter is sometimes considered as a part of an environmental problem as is in the case of resources depletion.

²The number of chemicals listed in the Chemical Abstract Service (CAS) Registry database, which is considered as the largest chemical database in the World.

³In 1998, US EPA extended the sector coverage for their TRI report, dramatically increasing the completeness of the database.

⁴In CEDA 3.0, any data involving SIC codes are first assigned to the most detailed set of SIC codes, which distinguish 1037 different industries, and then reclassified under a BEA code to preserve as far as possible the detail of the primary data.

⁵In reality, some of the passenger cars are used as a part of industrial activities by, for example, insurance carriers; likewise, some of the heavy-duty trucks and buses are used for private purposes. These overlaps were, however, not considered to be significant and were assumed to be canceled out.

⁶PM10 and PM2.5 have been distinguished.

⁷Some of the chemicals that are compiled in NET but are not included in these databases are identified and added to CEDA.

⁸These results also support, to some extent, the study by Ayres and Ayres (1998).

⁹Using the Census Bureau (2001) data, the relationship between the completeness of TRI and the proportion of small-to-medium sized establishments in each industry was examined. The results show that the two are negatively correlated.

¹⁰The coefficients of regression lie between 2.1 to 7.1, depending on the sector. Several significant differences between TRI 98 (i.e. for 1998) and NTI for 1996 are observed for SIC 49, Utilities, although there was relatively little change in technology or regulation between the two periods. Formaldehyde and chlorine emissions, for instance, are reported to be 57.7 and 23.0 tons, respectively, by TRI98, while NTI for 1996 reports, for the same chemicals, 15,965.5 and 1514.0 tons, respectively.

- ¹¹Land use data for the year 1998 were not available in the data sources considered, and 1997 data were used instead (USDA, 2002). According to trend analyses by USDA (2002), however, the pattern of land use for different activities has remained fairly stable and no readjustments were therefore made to estimate values for 1998.
- ¹²Furthermore, no statistics on land use were found that could be allocated to the detailed six-digit BEA industry level. As land use intensity in urban areas is considered relatively high, however, it is desirable to extend data coverage on urban use further, especially as impact assessment methods that can properly account for land use intensity become available.
- ¹³There are several ‘within-industry’ uses of transportation that are not visible in the input–output table. However, it has been assumed that utilization of transportation industry services reflects the relative magnitude of the transportation activities of each industry.
- ¹⁴However, it is notable that major progress has been made in LCIA to better take the spatial aspects into account (see, for example, Potting, 2000; Wegener Sleswijk, 2002).
- ¹⁵An international platform where these activities are lively discussed, developed and disseminated is the Life Cycle Initiative by the United Nations Environmental Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) (see, for example, Jolliet *et al.*, 2003b).
- ¹⁶See for example the European Pollutant Emission Register (EPER) <<http://eper.cec.eu.int/>>. For a list of national emission registers, see <http://eper.cec.eu.int/eper/National_links.asp?i=>, also for Japan see <<http://www.prrt.nite.go.jp/english/prtr-e.html>>, and for the USA <<http://www.epa.gov/ttn/chief/net/index.html>>.

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