Material Flow Analysis

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What is Material Flow Analysis?

"Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time."

Brunner and Rechberger, 2004

Applications of MFA: Industrial Ecology

- IE design principles related to MFA:
  - Controlling pathways for materials use and industrial processes
  - Creating loop-closing industrial practices
  - Dematerializing industrial output
  - Systematizing patterns of energy use
  - Balancing industrial input and output to natural ecosystem capacity

Applications of MFA: Environmental Management and Engineering

- Environmental impact statements
- Remediation of hazardous waste sites
- Design of air pollution control strategies
- Nutrient management in watersheds
- Planning of soil-monitoring systems
- Sewage sludge management

Applications of MFA: Resource and Waste Management

- Resource Management: Analysis, planning and allocation, exploitation, and upgrading of resources
- MFA uses in waste management
  - Modeling elemental compositions of wastes
  - Evaluating material management performance in recycling/treatment facilities
- Examples:
  - Regional material balances
  - Single material system analysis

Applications of MFA: Human Metabolism

- Metabolism of the anthroposhpere
- Key processes and goods
  - Inputs: water, food, building and transport materials
  - Outputs: sewage, off-gas, solid waste

The first application of MFA?

- Santorio Santorio (1561-1636)
- Measured human input and output
- Output weighs much less
- Hypothesis: output of "insensible perspiration"

MFA Objectives

- Delineate system of material flows and stocks
- Reduce system complexity while maintaining basis for decision-making
- Assess relevant flows and stocks quantitatively, checking mass balance, sensitivities, and uncertainties
- Present system results in reproducible, understandable, transparent fashion
- Use results as a basis for managing resources, the environment, and wastes
  - Monitor accumulation or depletion of stocks, future environmental loadings
  - Design of environmentally-beneficial goods, processes, and systems

MFA vs. LCA

- MFA is a method to establish an inventory for an LCA
  - Hence, LCA can be an impact assessment of MFA results
- LCA strives for completeness
  - As many substances as possible
- MFA strives for transparency and manageability
  - Limited number of substances

Types of Material Flow-Related Analysis

Type I		
a	b	c
Impacts per unit flow of		
substances	**materials**	**products**
e.g., Cd, Cl, Pb, Zn, CO_2, CFC	e.g., energy carriers, excavation, biomass, plastics	e.g., diapers, batteries, cars
within certain firms, sectors, regions		

Type II		
a	b	c
Throughput of		
firms	**sectors**	**regions**
e.g., single plants, medium and large companies	e.g., production sectors, chemical industry, construction	e.g., total throughput, mass flow balance, total material requirement
associated with substances, materials, products		

Uses of Material Flow Analyses

Type I

- **Development of environmental policy for hazardous substances**
- **Evaluation of product environmental impact**

Type II

- **Providing firm environmental performance data**
- **Derivation of sustainability indicators**
- **Development of material flow accounts for use in official statistics**

Definitions

- Material: substances and goods
- Substance: single type of matter (elements, compounds)
- Goods: substances or mixtures of substances that have economic values assigned by markets
  - Can include immaterial goods (energy, services, or information)
- Process: transport, transformation, or storage of materials (natural or man-made)
- Stocks: material reservoirs within the analyzed system

Definitions (cont.)

- **Flows: mass per time (link processes)**
- **Fluxes: mass per time and cross section**
- **Imports/exports: flows/fluxes across *system* boundaries**
- **Inputs/outputs: flows/fluxes across *process* boundaries**
- **System: set of material flows, stocks, and processes within a defined boundary**
- **Activity: set of systems needed to fulfill a basic human need (nourish, reside, transport, etc.)**

Generic MFA Procedure

- **Systems Definition**
  - **Target Questions: What are primary objectives?**
  - **Scope: Spatial, temporal, functional**
  - **System Boundary: Defines start and end of flows**
- **Process Chain Analysis: Defines processes using** *accounting and balancing*
  - **Mass balancing to determine inputs and outputs**
  - **Modeling may be applied**
- **Evaluation**
  - **May involve impact criteria**

Type Ia: Anthropogenic Copper Cycle

Generic System Boundary

Diagram removed due to copyright restrictions.

Figure in Graedel, T. E., et al. "Multilevel Cycle of Anthropogenic Copper." *Environmental Science and Technology* 38 (2004): 1242-1252.

China Copper Cycle, 1994 (Gg/yr)

Diagram removed due to copyright restrictions.

Figure in Graedel, T. E., et al. "Multilevel Cycle of Anthropogenic Copper." *Environmental Science and Technology* 38 (2004): 1242-1252.

North American Copper Cycle, 1994 (Gg/yr)

Diagram removed due to copyright restrictions.
Figure in Graedel, T. E., et al. "Multilevel Cycle of Anthropogenic Copper." *Environmental Science and Technology* 38 (2004): 1242-1252.

World Copper Cycle, 1994 (Gg/yr)

Diagram removed due to copyright restrictions.
Figure in Graedel, T. E., et al. "Multilevel Cycle of Anthropogenic Copper."
Environmental Science and Technology 38 (2004): 1242-1252.

What is the value of this analysis?

Type IIc: Anthropogenic Metabolism

Prehistoric

Breath
5.1

Image of caveman removed due to copyright restrictions.

Goods
6

Excreta
0.8

Stock
~0

Solid Waste
0.1

Modern

Off gas
19

Consumption
86

Sewage
61

Stock
260

Solid Waste
3

Units: tonnes/capita (stocks) or tonnes/capita/year

Direct material flows only

Source: Brunner and Rechberger, 2004

Anthropogenic Metabolism of Modern Man

Material Flows and Stocks for Selected Activities of Modern Man

Activity	Input t/(c yr)	Output, t/(c yr)			Stock t/c
		Sewage	Off Gas	Solid Residues	
To nourish	5.7	0.9	4.7	0.1	<0.1
To clean	60	60	0	0.02	0.1
To reside	10	0	7.6	1	100
To transport	10	0	6	1.6	160
Total	86	61	19	2.7	260

Type IIc: Economy-Wide Material Flows Metrics

Inputs

- DMI (Direct Material Input)=
  Domestic Extraction + Imports
- TMR (Total Material Requirement)=
  DMI + Domestic Hidden Flows + Foreign Hidden Flows

Outputs

- DPO (Domestic Processed Output)=
  Emissions + Waste =
  DMI – Net Additions to Stock – Exports
- DMO (Direct Material Output)=
  DPO + Exports
- TDO (Total Domestic Output)=
  DPO + Domestic Hidden Flows

Type IIc: Economy-Wide Material Flows Metrics (cont.)

Consumption

- **DMC (Direct Materials Consumption)= DMI - Exports**
- **TMC (Total Materials Consumption)= TMR – Exports – Hidden Flows from Exports**

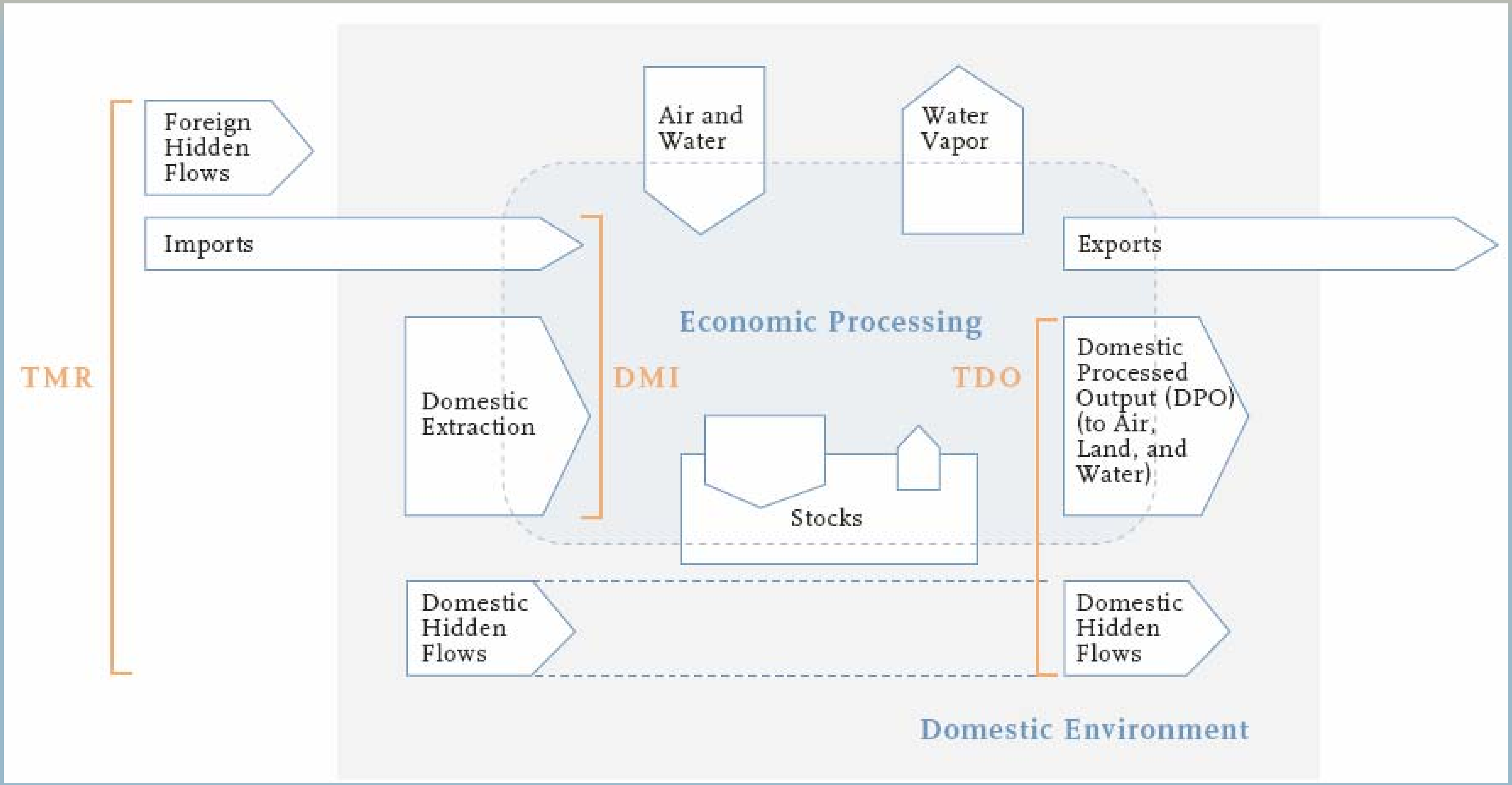
Balance

- **NAS (Net Additions to Stock)= DMI – DPO – Exports**
- **PTB (Physical Trade Balance)= Imports – exports**

Efficiency

- **Input or Output/GDP (Material Productivity)**
- **Unused/used (Resource efficiency of materials extraction)= Unused (hidden or indirect) / used (DMI) materials**

Economy-Wide Material Flows: Material Cycle



Regional Material Balances: Vienna, 1990s

Air: 36

Off-gas: 43

Water: 147

Sewage: 144

Stock: 350

Fossil Fuels: 2

Construction Materials and Consumer Goods: 12-18

Export Goods: 3

Solid Wastes: 3

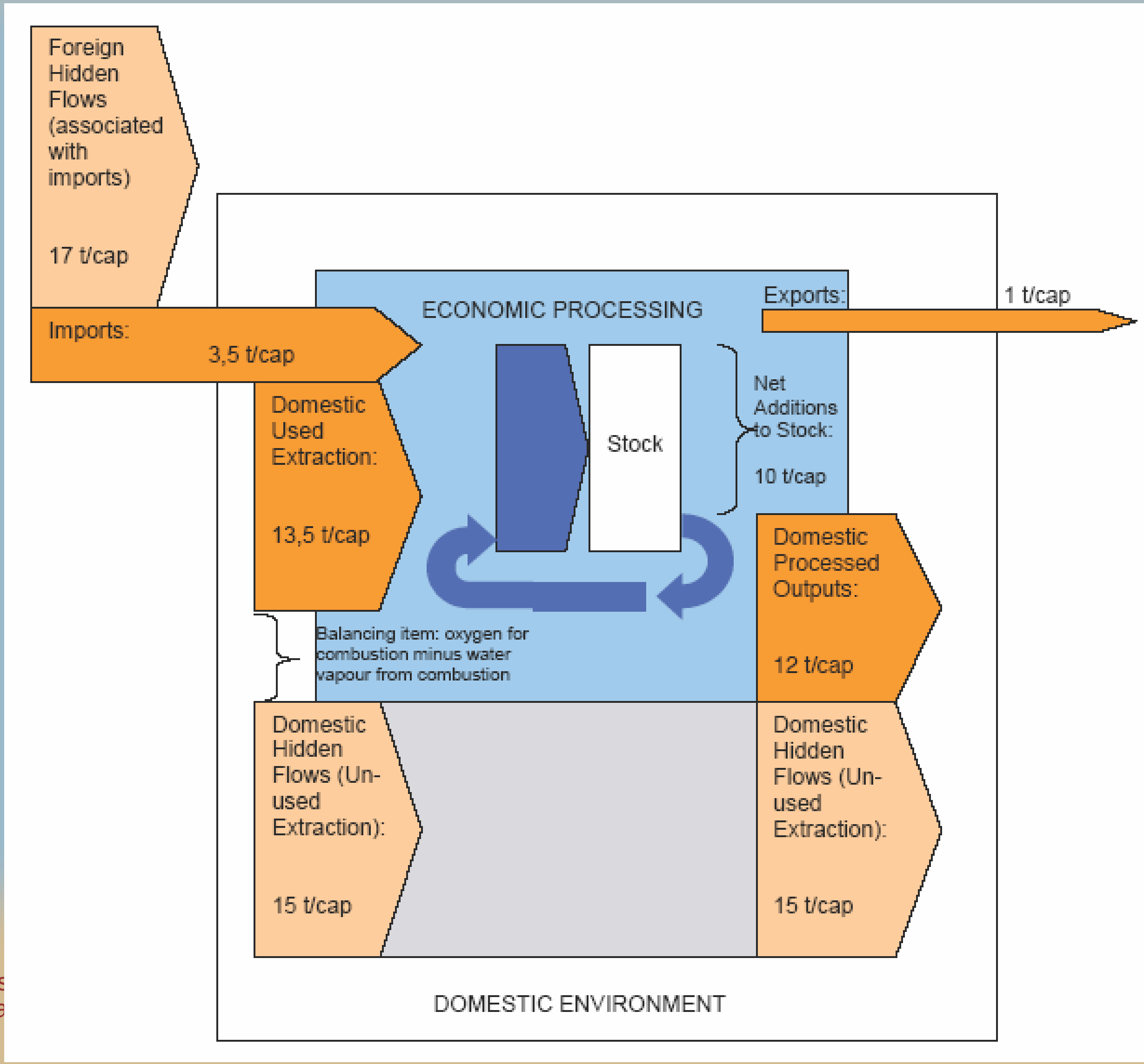
Municipal Solid Wastes: 0.3

Photo courtesy of Premshree Pillai.

Units: tonnes/capita (stocks) or tonnes/capita/year

Source: Brunner and Rechberger, 2004

EU Economy-Wide Material Flows: 1990s (t/c/yr)



US Material Flows, 1990 (Mt)

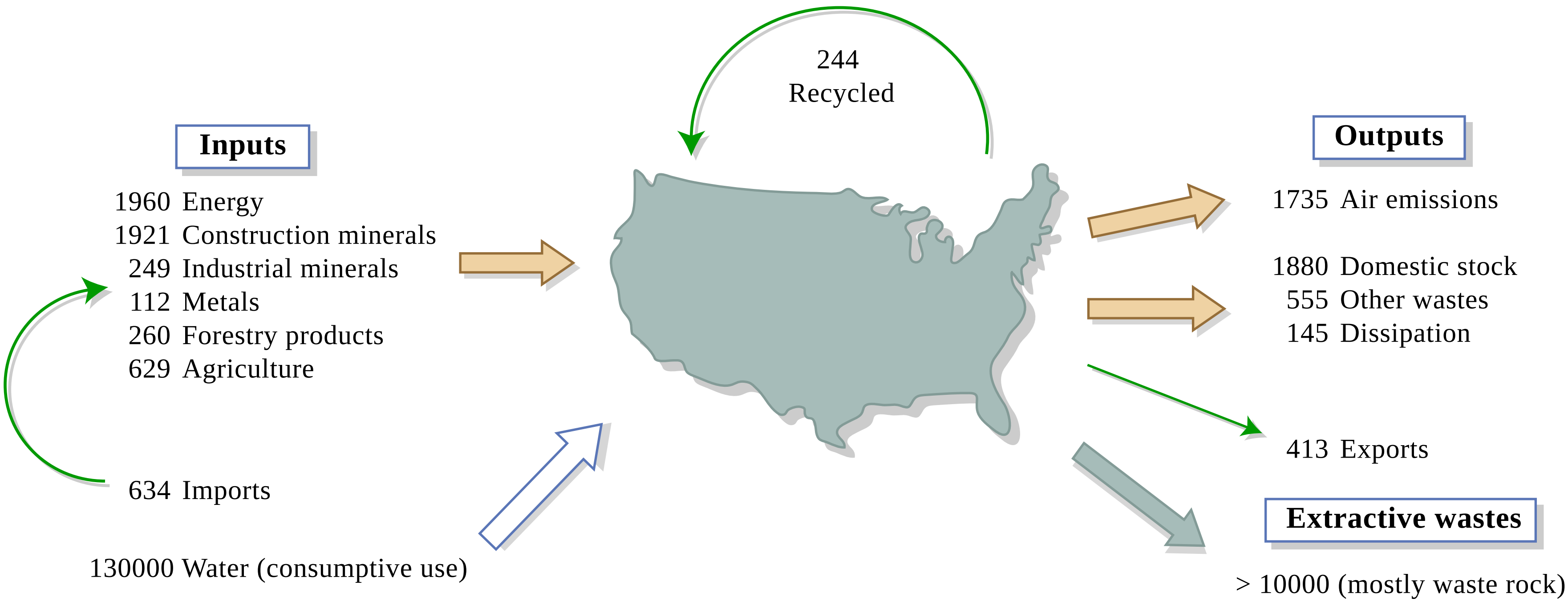
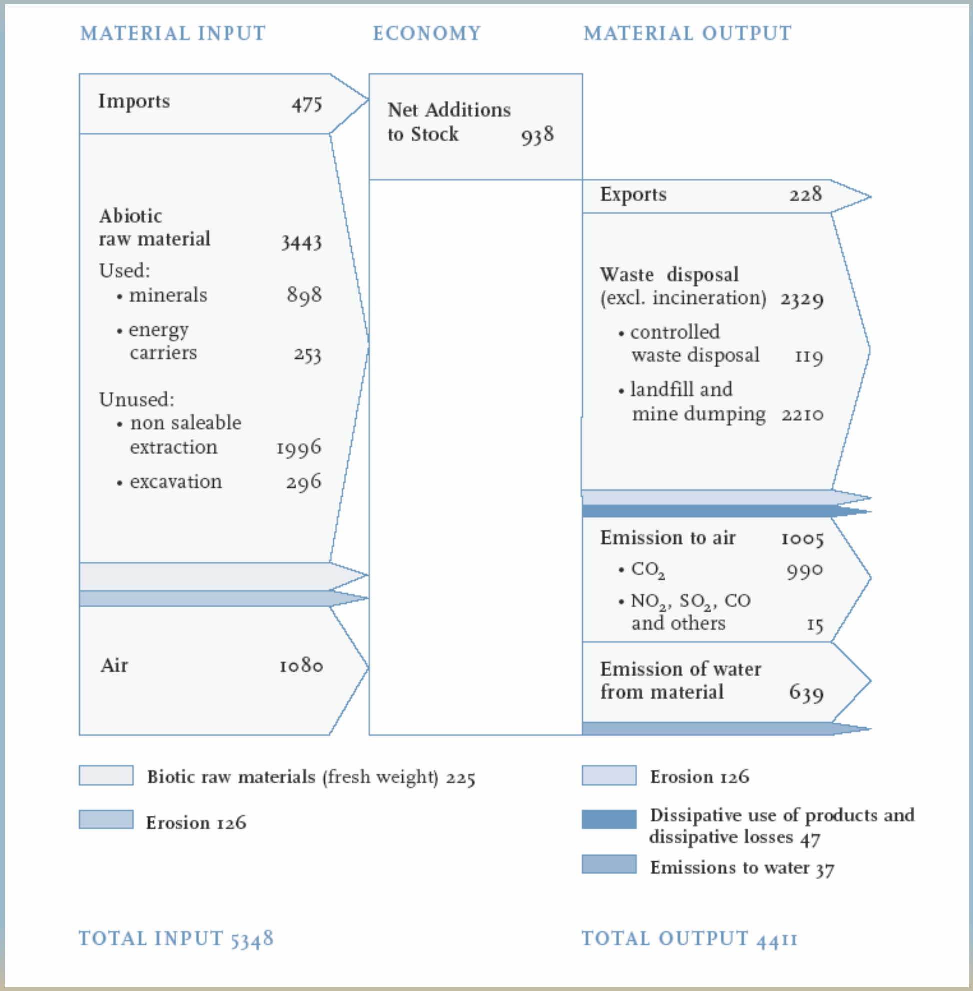


Figure by MIT OCW.

Material Flow Balance of Germany, 1996 (Mt)



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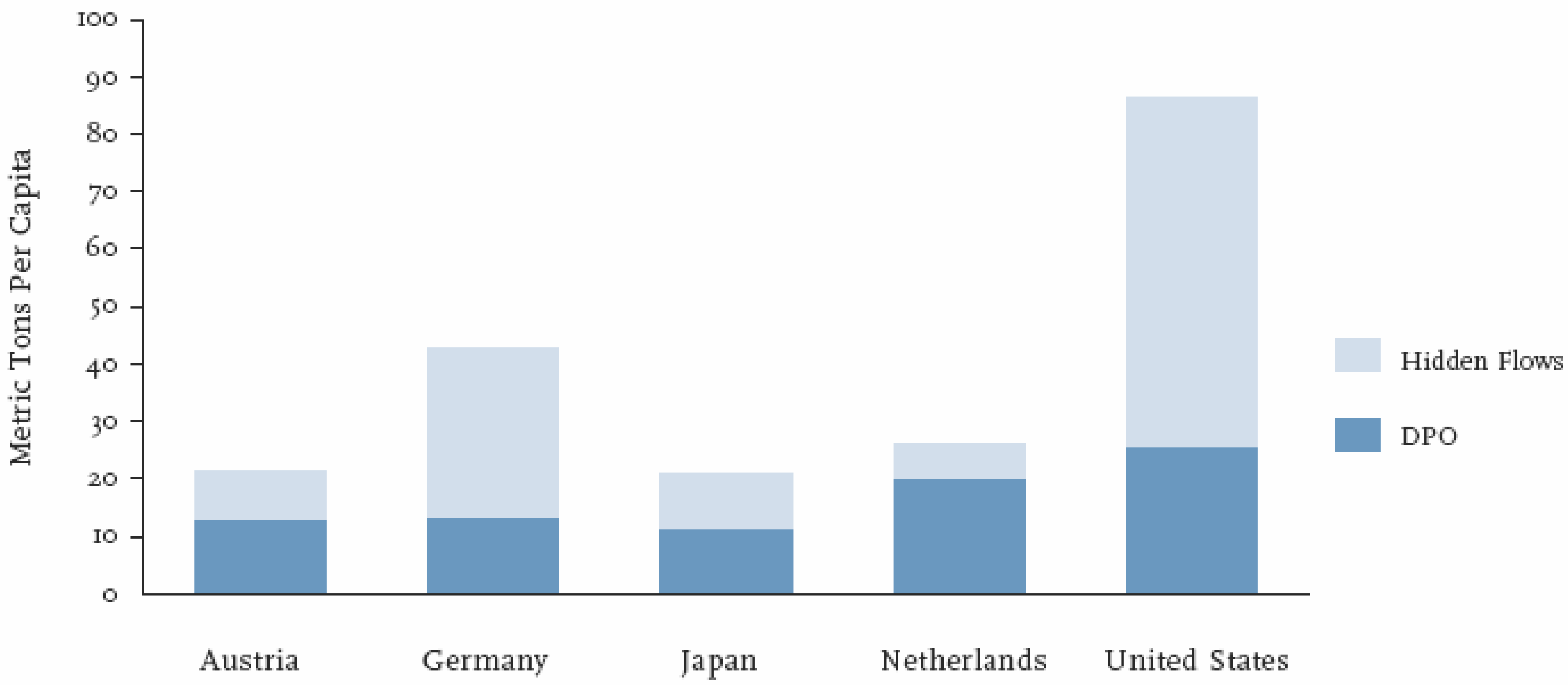
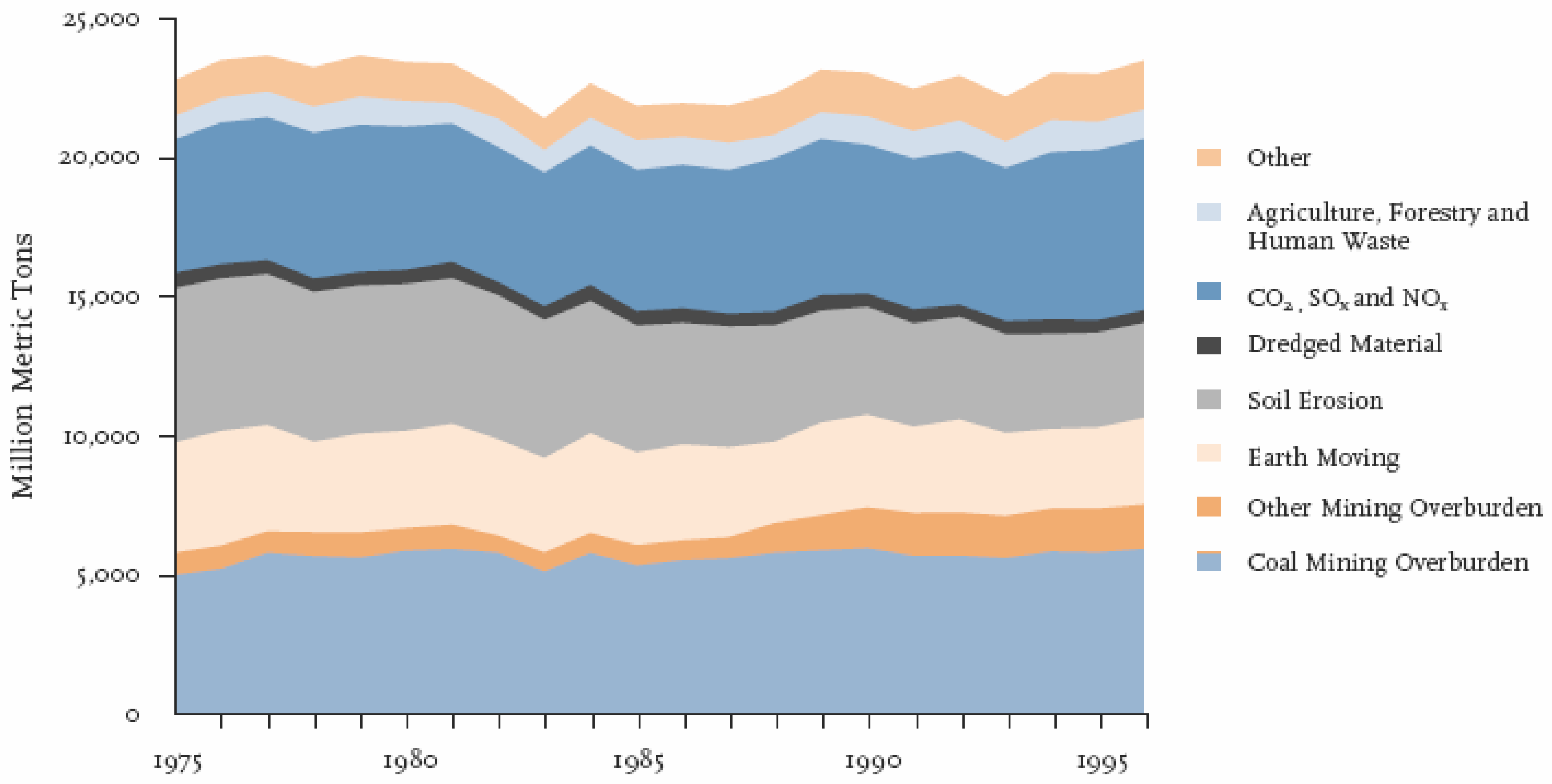
Total Domestic Output, 1996



US TDO Composition



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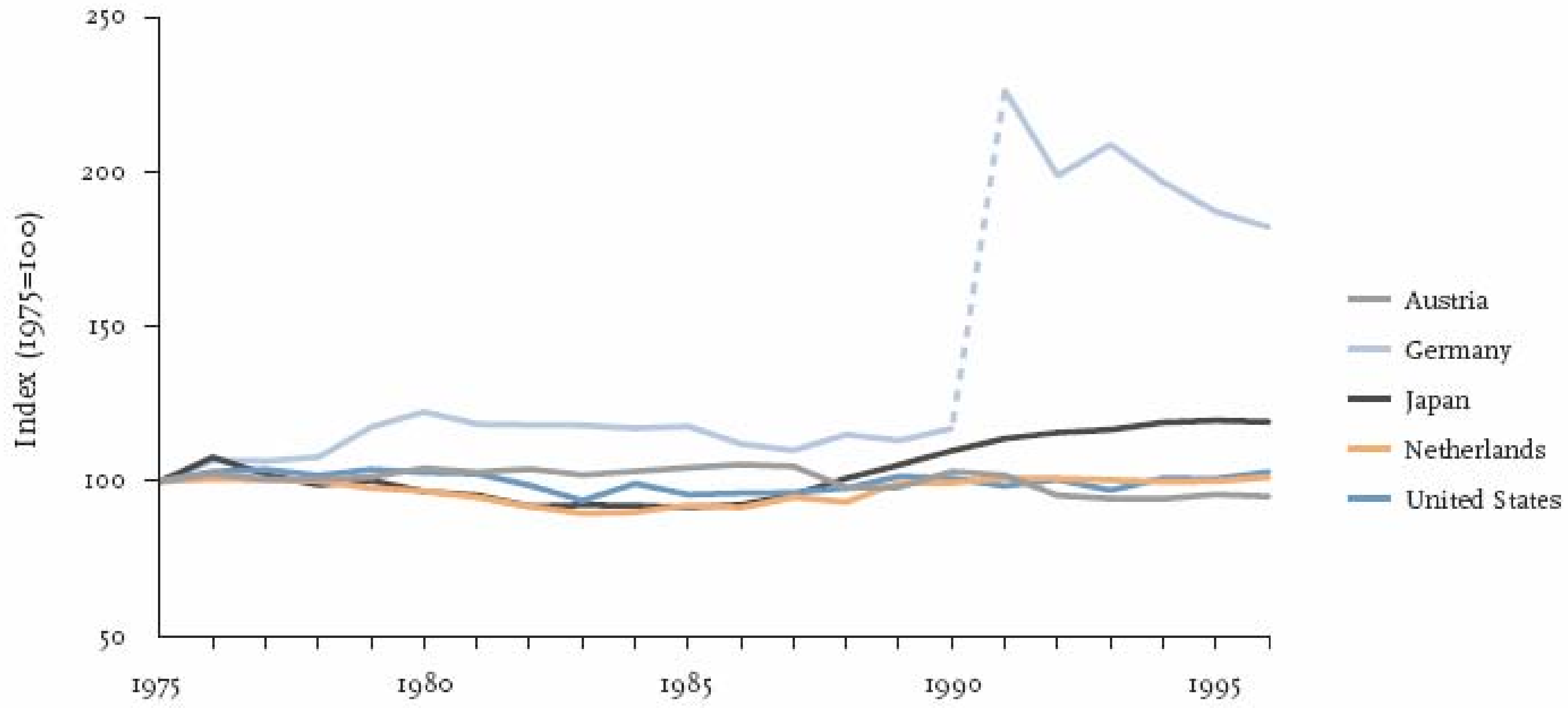
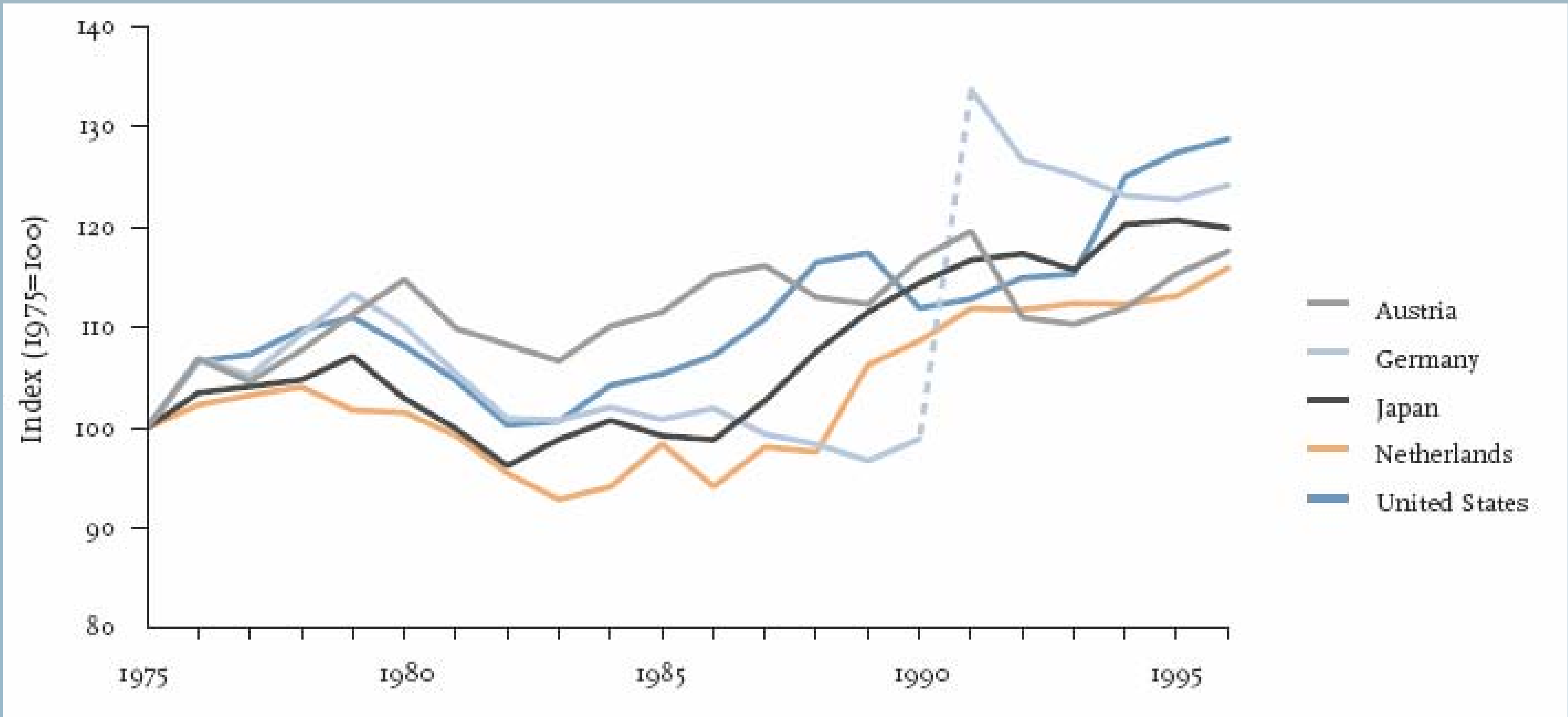
Relation Between Monetary and Material Output Flows, 1996

Country	GDP		DPO		TDO	
	Billion $US	Ratio	Million Metric Tons	Ratio	Million Metric Tons	Ratio
Austria	235.3	1.0	100.8	1.0	171.3	1.0
Netherlands	410.5	1.7	281.3	2.8	381.1	2.2
Germany	2,446.6	10.4	1,074.7	10.7	3,492.2	20.4
Japan	5,338.9	22.7	1,406.5	14.0	2,632.1	15.4
United States	7,390.6	31.4	6,773.8	67.0	23,261.0	135.8

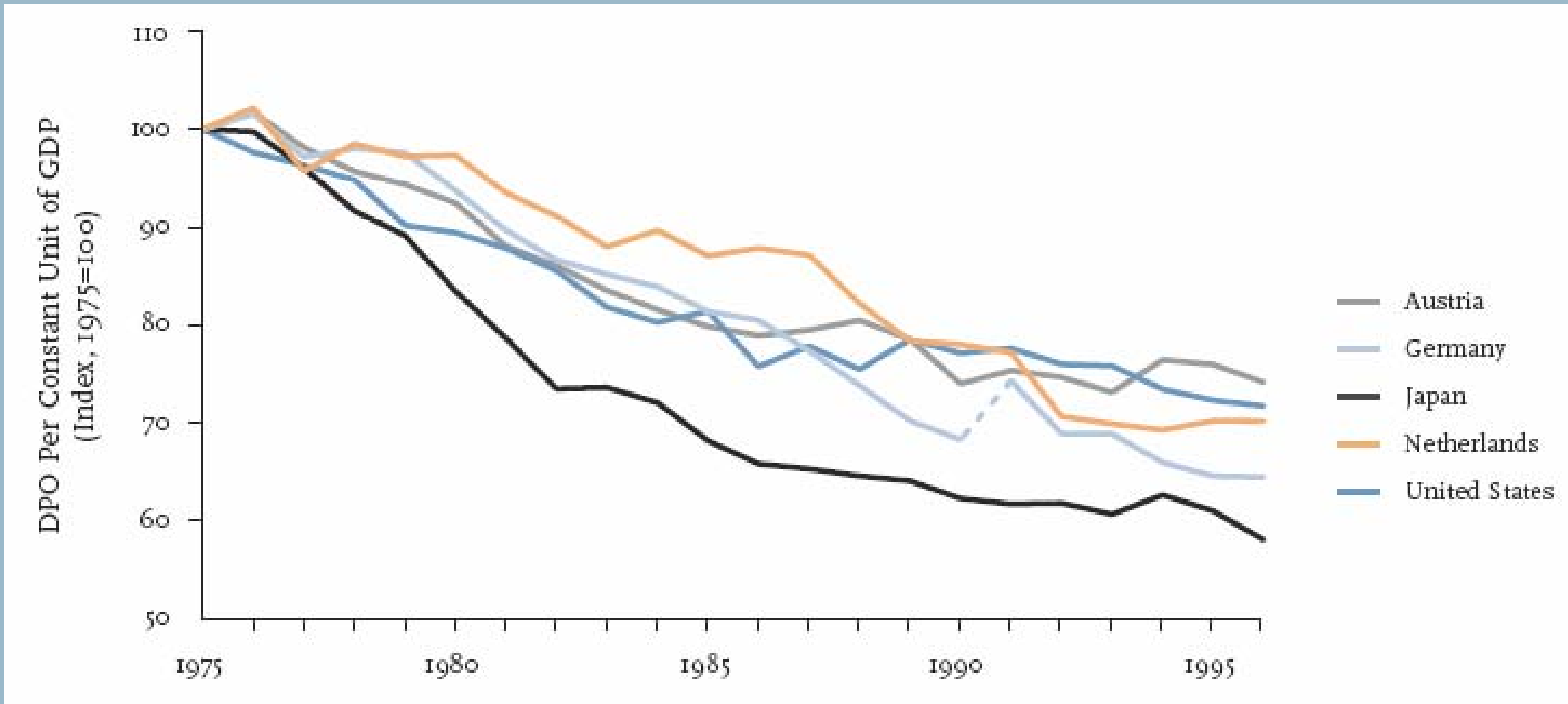
Trends in TDO



Domestic Material Output (DPO)



Material Outflow Intensity (DPO/GDP)



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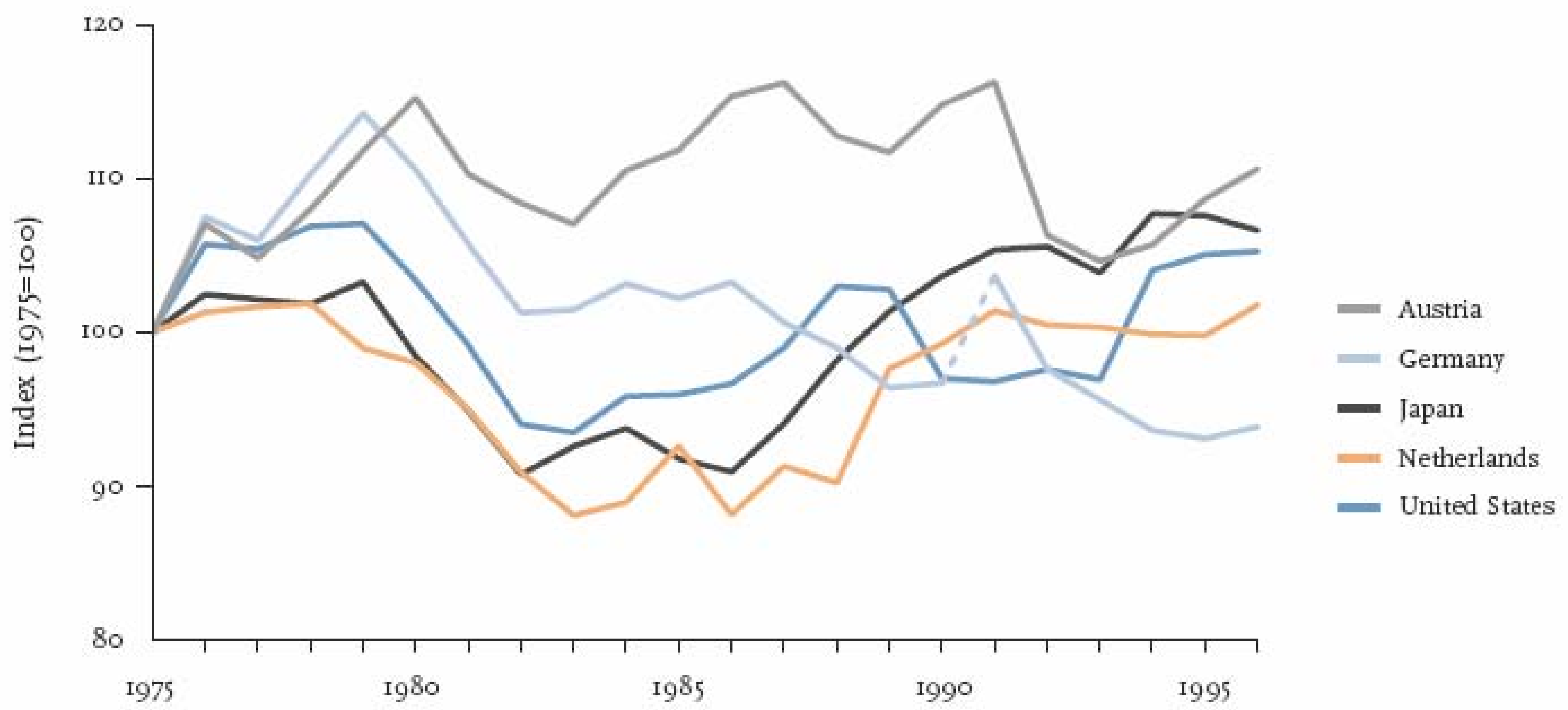
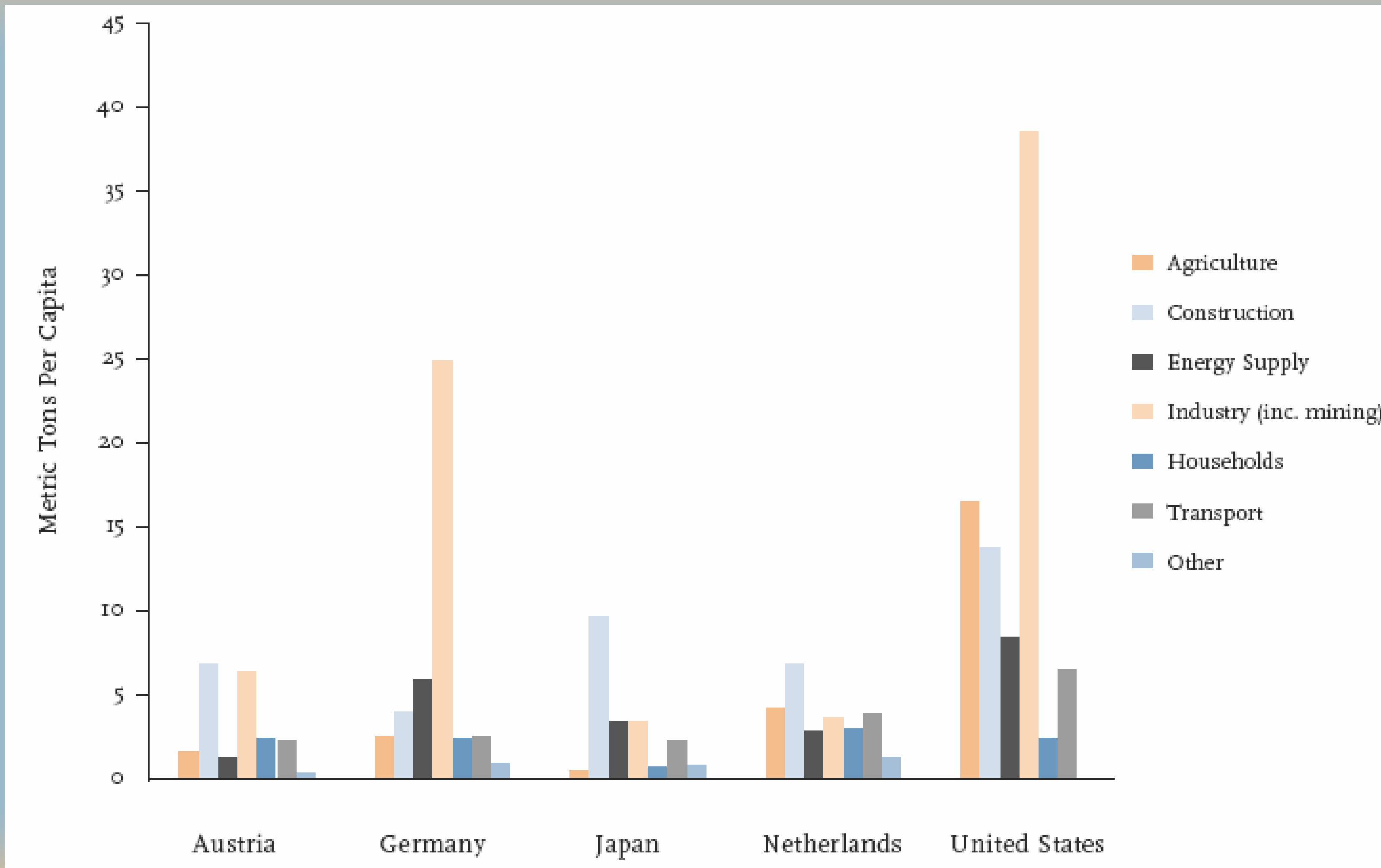
Material Outflow Intensity (DPO per Capita)



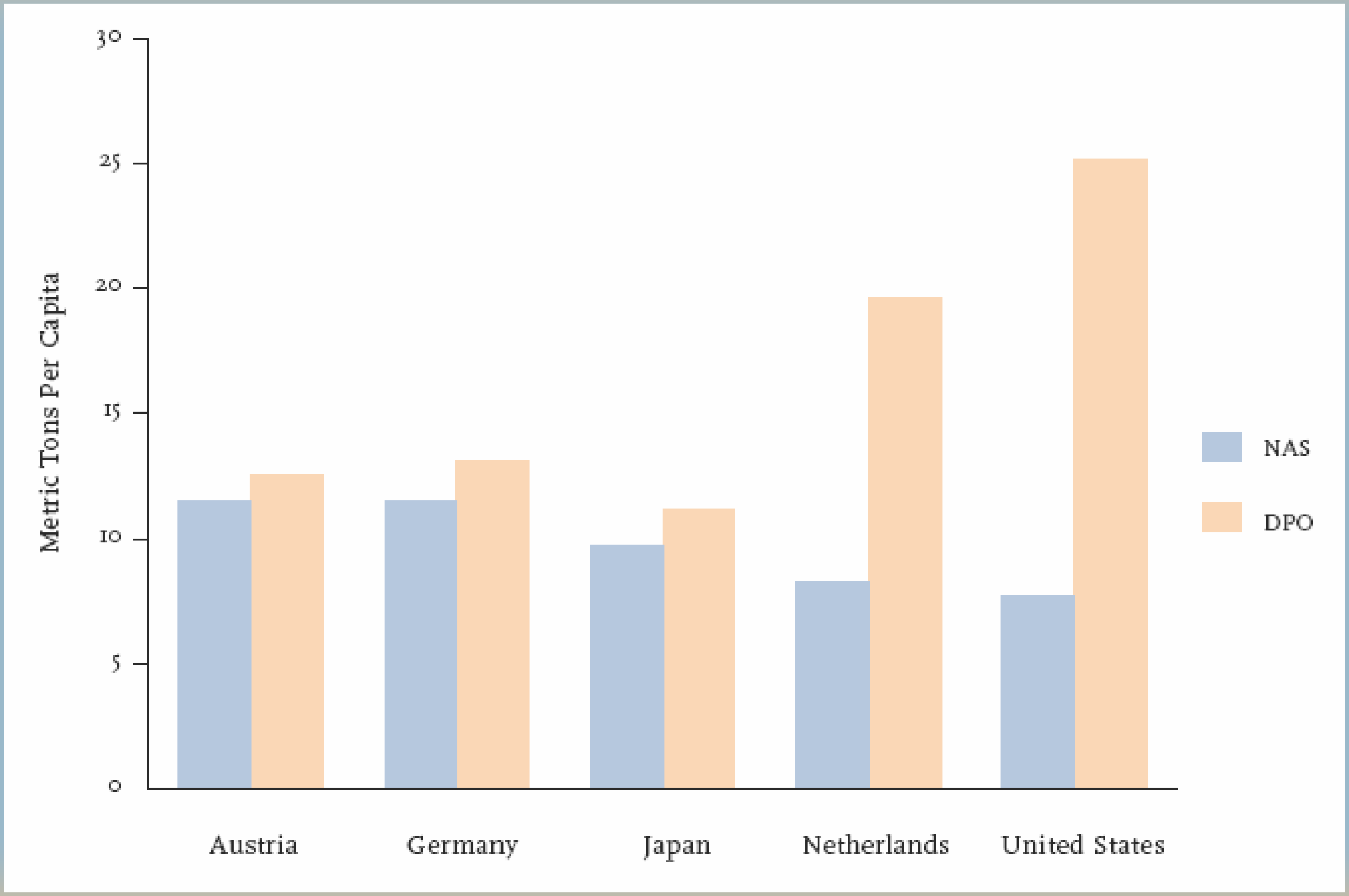
Population, Economic, and DPO Trends

Country		Population (millions)	DPO (million metric tons)	GDP (own currency *See notes*)	DPO/GDP (metric tons per million constant monetary units, own currency)	DPO/Capita (metric tons per capita)
Austria	1975	7.6	85.7	1,441.0	0.059	11.3
	1996	8.1	100.8	2,415.0	0.042	12.5
	% change	+6	+18	+68	−29	+10
Germany[1]	1975	61.8	865.3	1,838.5	0.47	14.0
	1996	81.8	1,074.7	3,541.5	0.30	13.1
	% change	+32	+24	+93	−36	−6
Japan	1975	111.9	1,173.0	244.3	4.80	10.5
	1996	125.9	1,406.5	504.4	2.78	11.2
	% change	+13	+20	+106	−42	+7
Netherlands	1975	13.6	242.6	413.0	0.59	17.8
	1996	15.5	281.3	667.6	0.42	18.1
	% change	+14	+16	+62	−29	+2
United States	1975	220.2	5,258.7	4,253.9	1.24	23.9
	1996	269.4	6,773.8	7,390.6	0.92	25.1
	% change	+23	+28	+74	−26	+5

Economic Sectors' Contribution to TDO



NAS and DPO, 1996



Key Findings from "Weight of Nations"

- Industrial economies are becoming more efficient in their use of materials, but waste generation continues to increase.
- One half to three quarters of annual resource inputs to industrial economies are returned to the environment as wastes within a year.
- Outputs of some hazardous materials have been regulated and successfully reduced or stabilized but outputs of many potentially harmful materials continue to increase.
- The extraction and use of fossil energy resources dominate output flows in all industrial countries.
- Physical accounts are urgently needed, because our knowledge of resource use and waste outputs is surprisingly limited.