Material Flows and Economic Growth in Developing China

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Keywords

China
economy-wide material flow accounting and analysis (EW-MFA)
industrial ecology
industrial metabolism
resource use indicators
sustainability

Summary

The concept of sustainable development concerns not only the natural environment but also human societies and economies. The method of economy-wide material flow accounting and analysis (EW-MFA) is internationally recognized as a valuable tool for studying the physical dimensions of economies. EW-MFA has been carried out in many industrialized countries, but very little work has been done for developing China; this article can be regarded as one of the first attempts to study China's economy in terms of material flows. In this article we have compiled material flow accounts for China during the time series 1990 to 2002 and derived indicators associated with international comparison. Results show that the annual material consumption of China's economy continuously increased except for a slump around 1998, whereas the material efficiency exhibited a three-phase trend reflecting different macropolicies of the Eighth, Ninth, and Tenth Five-Year Plans implemented by the central government. Based on this experience with EW-MFA for China, suggestions for methodology development and further research are given for improving EW-MFA as a more effective tool for environmental management.

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Introduction

During the past century, human society has achieved great success in economic growth. But economic growth has neglected the truth that natural resources are not infinitely provided by the environmental system. Thus more and more serious resource-related and environmental problems are emerging. Studying the physical dimensions of the economy is one way to possibly find a solution for a problem such as sustainable development. During the past 15 years, material and energy flow analysis have emerged as significant approaches to tracking the flows of matter and energy and to comparing the natural ecosystem and the industrial system in a study of "industrial metabolism" (Ayres 1994; Erkman 1997). A number of studies have been presented for industrialized countries (e.g., Adriaanse et al. 1997; Matthews et al. 2000; Eurostat 2002) and for transition economies (e.g., Hammer and Hubacek 2002; Mündl et al. 1999; Ščasný et al. 2003; Amann et al. 2002; Giljum 2004). For China, some preliminary research studies have been carried out (Chen and Qiao 2001; Xu and Zhang 2004, 2005; Liu et al. 2005; Xu et al. 2005).

In 1994, a plan for China's sustainable development was presented in *China's Agenda 21—White Paper on China's Population, Environment, and Development in the 21st Century*.[1] Sustainable development is regarded as an increasingly important issue by China's government and public. This study focuses on the physical dimensions of China's economy, using the method of economy-wide material flow accounting and analysis (EW-MFA). This method has received increasing recognition for its ability to make the socioeconomic system physically known. China's economy has been rapidly growing since the early 1990s, with gross domestic product (GDP) growing around 10% annually. This illustrious economic achievement rests, though, on a vast amount of material expended, severe exhaustion of natural resources, and serious deterioration of the environment. Although the increase in use of materials and energy is an essential and unavoidable prerequisite for the transition to an industrialized economy, it is still very important for sustainable development to find a way to consume limited natural resources with maximum efficiency.

This article first provides a brief introduction to the method of EW-MFA. The main part of the article is devoted to the presentation and discussion of the main EW-MFA indicators for China during the time series for 1990 to 2002. Next, suggestions for future research are presented. In the final section, conclusions for the article are drawn.

Economy-wide Material Flow Accounting and Analysis

The EW-MFA method considers the economic system as an embedded subsystem of the ecosystem, giving us new tools for monitoring progress toward the development of a more eco-efficient economy and long-term sustainability. In the EW-MFA framework, materials are tracked from the extraction of natural resources to stocks and accumulation within the economy, and finally to waste and emission into the environment. The physical amounts of materials in different phases of industrial processing are totalled, and a set of physical indicators are also developed. Using EW-MFA indicators, the physical dimension of an economic system can be evaluated and analyzed.

Within the input side of the economic system, material flows are classified by EW-MFA as the following: (a) Domestic extraction used (DEU) refers to the materials that can be directly observed to enter the economic system from the domestic environment. (For definitions of the acronyms used throughout this article, see table 1.) These materials consist of fossil fuels, minerals, and biomass. (b) Imports consist of the materials imported from other countries. (c) Unused domestic extraction (UDE) is defined as the materials that are extracted from the domestic environment but do not enter any economic system (e.g., cover material or overburden from mining or residuals from harvest in agriculture). (d) Indirect flows associated with imports (IFI) are calculations of upstream material requirements associated with imports. For EW-MFA, indirect flows contain two components: upstream indirect flows—expressed as the raw material equivalents (RME)—of the imported

Table 1 Acronyms used in this article

DEU	Domestic extraction used: the materials that can be directly observed to enter the economic system from the domestic environment.
DMC	Domestic material consumption: the total amount of material directly used in an economy.
DMI	Direct material input: the input of materials for use in the economy.
DPO	Domestic processed output: the materials consumed domestically within the accounting period.
EU-15	The 15 countries making up the European Union before 1 May 2004.
EW-MFA	Economy-wide material flow accounting and analysis.
GDP	Gross domestic product.
IFI	Indirect flows associated with imports: calculations of upstream material requirements associated with Imports.
NAS	Net addition to stock: the physical growth of the economy.
PTB	Physical trade balance: the difference between the amounts of Imports and Exports.
RME	Raw material equivalents of the imported products.
TDO	Total domestic output (TDO): the domestic processed output plus the unused domestic extraction.
TMR	Total material requirement: the total material base of the economy.
UDE	Unused domestic extraction: the materials that are extracted from the domestic environment but do not enter any economic system.

products and upstream indirect flows of unused extraction associated with this RME.

In the economic system, material inputs are transformed into (a) net additions to stock (NAS), which are the materials accumulated within the socioeconomic system, such as infrastructure and durable goods; (b) domestic processed output (DPO), which is defined as the materials consumed domestically within the accounting period (in most cases 1 yr) and thus crossing the system boundary back to the environment as waste, emissions, and dissipative use or loss that is dispersed into the environment as a deliberate, or unavoidable (with current technology), consequence of product use; (c) exports, which consist of materials exported to other countries.

The material flow categories and some main indicators provided by EW-MFA are presented in figure 1. A number of aggregated physical indicators can be derived from material flow accounting, which can be classified into input, output, and consumption categories. The detail of these indicators will be described in the following section. The physical indicators can be calculated either absolutely or relatively by population size (per capita) and economic performance (per unit GDP).[2] Indicators can be used to express material efficiency (units of GDP per unit of material indicator) or material intensity (the mathematical inverse of material efficiency). If input indicators are related to population size, the result also measures the material intensity. The decline of material intensity and growth of material efficiency is a necessary feature of sustainable development, but not sufficient.

The EW-MFA indicators of China's economy from 1990 to 2002 are studied in this article. The DEU data for fossil fuels, net metal-related ores, biomass, and DPO can be gained from special yearbooks published officially. These yearbooks are the 1990–2002 *China Statistical Yearbook*, *China Steel Yearbook*, *China Nonferrous Metal Industry Yearbook*, *China Energy Statistical Yearbook*, and *China Environment Yearbook* (see National Bureau of Statistics of China [1991–2003]; Editing Committee of China Steel Yearbook [1991–2003]; Editing Committee of China Nonferrous Metal Industry Yearbook [1991–2003]; Editing Committee of China Energy Statistical Yearbook [1991–2003]; and Editing Committee of China Environment Yearbook [1991–2003]). For biomass data, particularly, the online database provided by the Food and Agriculture Organization of the United Nations is also used as a supplement (FAO 2005). For some data that are missing

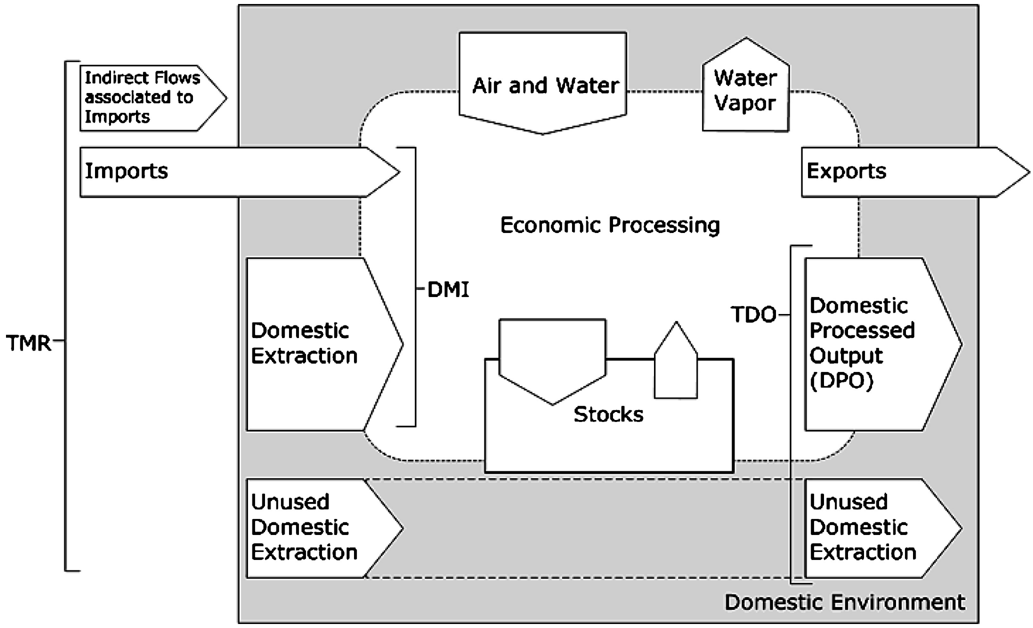

Figure 1 Material flow categories and main indicators in the economy-wide material flow accounting and analysis (EW-MFA) method (adapted from Matthews et al. 2000). TMR = total material requirement; DMI = direct material input; TDO = total domestic output. DMI = domestic extraction + Imports; TMR = DMI + UDE + IFI; NAS (net addition to stock) = DMI − DPO − Exports; TDO = DPO + UDE.

or are provided in nonphysical units, a good deal of work is required to estimate them. The detailed methods for dealing with these data are as follows: (a) The UDE of fossil fuel was calculated on the basis of coefficients provided by the Wuppertal Institute for Climate, Environment and Energy (2003) in Germany. (b) The UDE of ferrous and nonferrous metal-related ores was calculated from specific data provided by the *China Steel Yearbook* and the *China Nonferrous Metal Industry Yearbook*, consisting of the amount of tunneling, overburden mining, and other unused flows. (c) The DEU and UDE of mass construction minerals were estimated from the data of yearly products of cement and flat glass and the area of construction completion. The coefficients were provided by Mo (2003) and Chen (2005). (d) The weights of imports and exports mostly consisted of foodstuff, steels, coal, oil, and so forth, for which the physical data were provided by the 1990–2002 *Yearbook of China's Foreign Economic Relations and Trade* (see Editing Committee of Yearbook of China's Foreign Economic Relations and Trade [1991–2003]), whereas other minor flows having only monetary data were ignored. (e) IFI was not calculated, due to the lack of data and methods. (f) The amount of carbon dioxide emission, which makes up a large proportion in the output side, was provided by the online database of the Statistics Division of the United Nations (UNSD 2005). The weight of oxygen in carbon dioxide was calculated with the stoichiometric formula. (g) The amounts of by-products from agriculture, direct uptake by livestock animals, and nonmarketed animal fodder were calculated from the data provided by the 1990–2002 *Chinese Animal Husbandry Yearbook* (see Editing Committee of Chinese Animal Husbandry Yearbook [1991–2003]). (h) The weight of water used was not included in the accounting framework because of its considerably larger quantity than that of other materials. (i) A gap of missing data caused by changes in statistical rules was estimated by mathematic interpolation methods.

As with most countries in the world, China does not have any official statistical framework for physical materials. Thus, a lot of physical data in EW-MFA accounting are estimated from

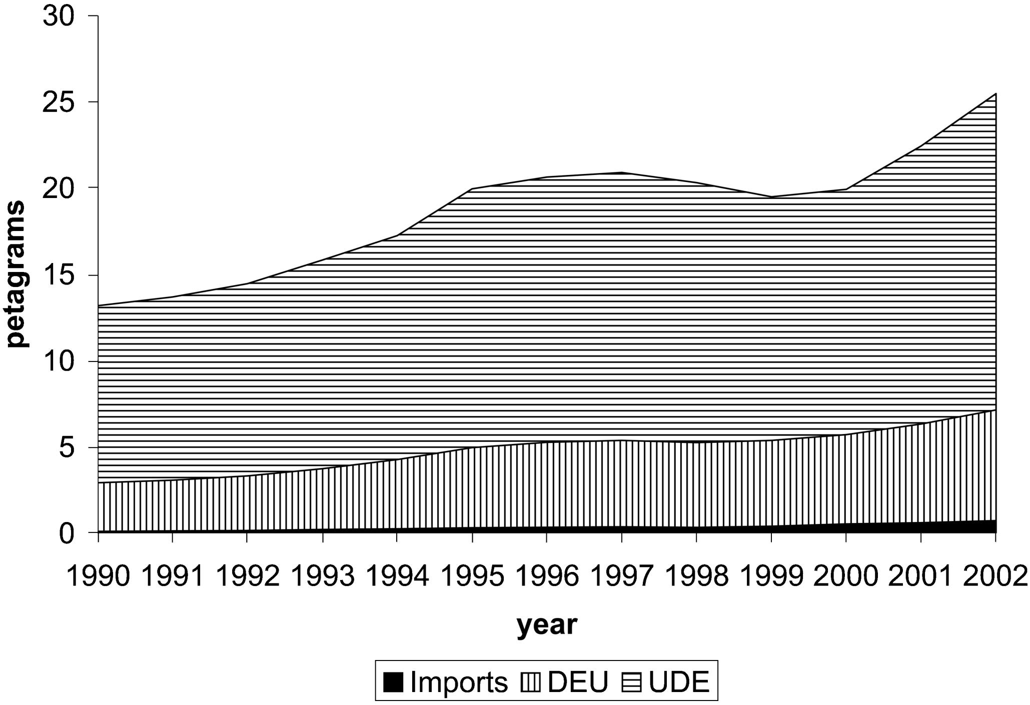

Figure 2 Input indicators for China from 1990 to 2002, in petagrams. UDE = unused domestic extraction; DEU = domestic extraction used; DMI = direct material input; TMR = total material requirement. One petagram (Pg) = one billion tonnes (10^9 t) = 10^{12} kilograms (kg, SI) ≈ 1.102 × 10^9 short tons.

Table 2 Input indicators and real GDP based on 2002 prices for China (in petagrams and billion ¥)

Year	*DEU*	*Imports*	*UDE*	*DMI*	*TMR*	*GDP*
1990	3	0.1	10	3	13	3,448
1991	3	0.1	11	3	14	3,765
1992	3	0.2	11	3	14	4,300
1993	4	0.2	12	4	16	4,880
1994	4	0.3	13	4	17	5,495
1995	5	0.3	15	5	20	6,072
1996	5	0.3	15	5	21	6,655
1997	5	0.4	16	5	21	7,241
1998	5	0.3	15	5	20	7,807
1999	5	0.4	14	5	19	8,365
2000	5	0.5	14	6	20	9,034
2001	6	0.6	16	6	22	9,711
2002	6	0.7	18	7	25	10,517

Note: Input indicators in petagrams (Pg; One billion tonnes); GDP in billion ¥ (Chinese yuan renminbi). One petagram (Pg) = one billion tonnes (10^9 t) = 10^{12} kilograms (kg, SI) ≈ 1.102 × 10^9 short tons. DEU = domestic extraction used; UDE = unused domestic extraction; DMI = direct material input; TMR = total material requirement; GDP = gross domestic product.

previous statistics data, most of which are in monetary units. The data quality should be improved in future research. The estimates used in this study, though, can satisfy the data requirement for such research on an economy-wide system, because information on most of the significant materials, such as fossil fuels and metal minerals, can be obtained directly.

Results and Discussion

In this article, material flow accounting for China from 1990 to 2002 has been applied. In this section, some analysis will be carried out based on indicators concerning material inputs, outputs, and consumption. The EW-MFA results for some industrialized countries are compiled to compare them with those for China.

Material Inputs

The main indicators on the input side are direct material input (DMI) and total material requirement (TMR). DMI measures the input of materials for use in the economy. DMI materials are used in production and consumption activities, which are of economic value. DMI equals DEU plus imports. TMR measures the total material base of the economy. TMR equals DMI plus UDE and IFI. In this study, the calculation of TMR excludes IFI (due to the lack of IFI data and methods), as previously mentioned. Table 2 and figure 2 show the absolute measurements of DMI and TMR for China's economy from 1990 to 2002.

In figure 2, DMI and TMR show continual increases from 1990 to 2002, excluding transitory slumps in 1998 and 1999. DMI grew from 3 petagrams (Pg; one billion tonnes) in 1990 to 7 Pg in 2002,[3] with an average annual increase of 7.75%. TMR grew from 13 Pg in 1990 to 25 Pg in 2002, with an average annual growth rate of 5.64%. In 1998, TMR began to decrease, from 21 Pg in 1997 to 20 Pg, and then to 19 Pg in 1999, and then began growing again in 2000. In that same period, China's economy grew continuously by an average of 9.74% annually—indicated by real GDP and based on 2002 prices (see table 2). The continuous increase of both DMI and TMR shows evidence that the extremely high rate of growth of China's economy is bringing on an almost unceasing increase of material consumption in China. Regarding the transitory slumps in 1998, not only DMI and TMR, but also the subindicators of DEU, imports, and UDE had the same slumps at the same time.

From 1990 to 2002 the patterns of variation of DMI and TMR can be divided into three phases, as follows: (a) from 1990 to 1995, DMI and TMR grew regularly at respective average rates of 12.53% and 8.64% annually; (b) from 1995 to 1999, DMI and TMR climbed the scale for a short period and then decreased back to the initial level before the rise; (c) from 1999 to 2002, DMI and TMR began to grow again at high rates, especially from 2000 to 2002. The annual average growth rates for DMI and TMR are, respectively, 11.90% and 13.05%.

During the first and third phases, annual growth of material inputs is higher than annual economic growth indicated by GDP. During the referenced phases, the material requirement per unit of economic growth of China is increasing. It can be concluded that the material efficiency of China's economic system was not improved during either of these phases. During a given single phase, the material consumption intensities indicated by DMI and TMR have nearly the same trend. The material consumption intensity is also sensitive to those different phases. For example, DMI and TMR changed only slightly before and including 2000. After 2001, though, DMI and TMR began to grow at instantly high rates. It is important to stress that we cannot easily tell whether the higher or lower growth rate of material consumption intensity is good or bad. For China, we cannot expect a developing country as such to dematerialize during this transition period. High intensity of material consumption is an essential prerequisite for industrialization. The amount of UDE plays a significant role in comparison with the DMI in TMR. The ratio of TMR to DMI shows a continual decrease from 1990 to 2002. In 2002, the ratio of TMR to DMI was 3.56, which means 3.56 tonnes of material are completely removed where only 1 tonne of material is used in the economic production process. The progressive decline of the ratio of TMR to DMI shows an increasing development of material efficiency, which will be discussed in more detail later.

Components of DMI and TMR include fossil fuels, metal-related minerals, industrial and construction minerals, and biomass. Figures 3 and 4 present the quantitative and proportional variation patterns of DMI components. Fossil fuels consist of oil, coal, and natural gas. Metal-related minerals consist of metal ores and other minerals used in ferrous and nonferrous metallurgy industries, such as clay, fluorite, and dolomite. These related minerals are not calculated in subsequent components of industrial and construction minerals, which comprise various nonmetal minerals for industrial process and construction. Biomass includes harvests and quarries from agriculture, forestry, fishing, and hunting.

From Figures 3 and 4, it can be found that the total amounts of metal minerals in DMI have approximately the same pattern of variation. Biomass in DMI grew continuously in amount but stayed proportionally in the range of 25%. Fossil fuels played an important role in DMI components for the majority of the time during the

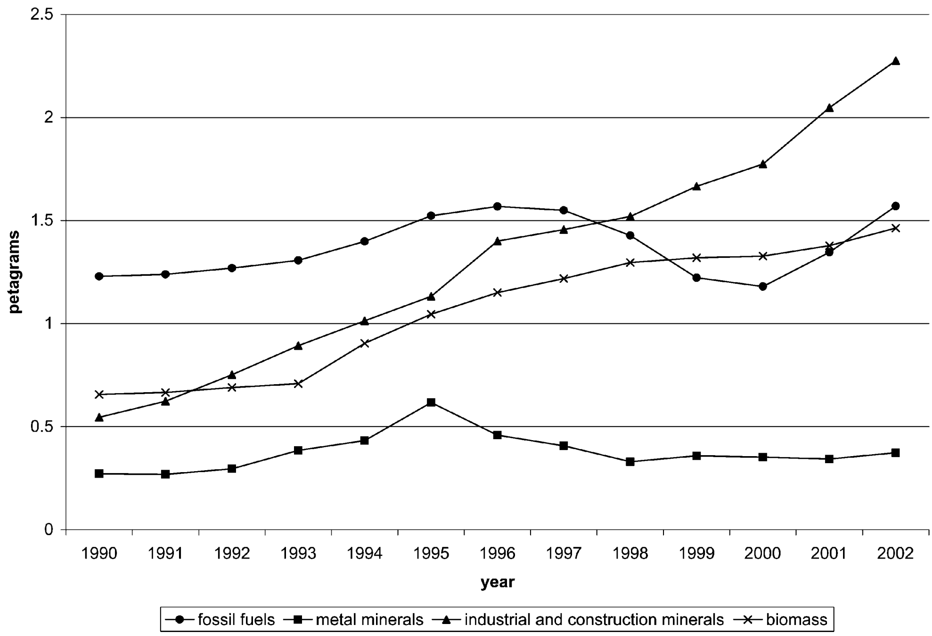

Figure 3 Direct material input (DMI) components for China from 1990 to 2002, in petagrams (Pg; one billion tonnes).

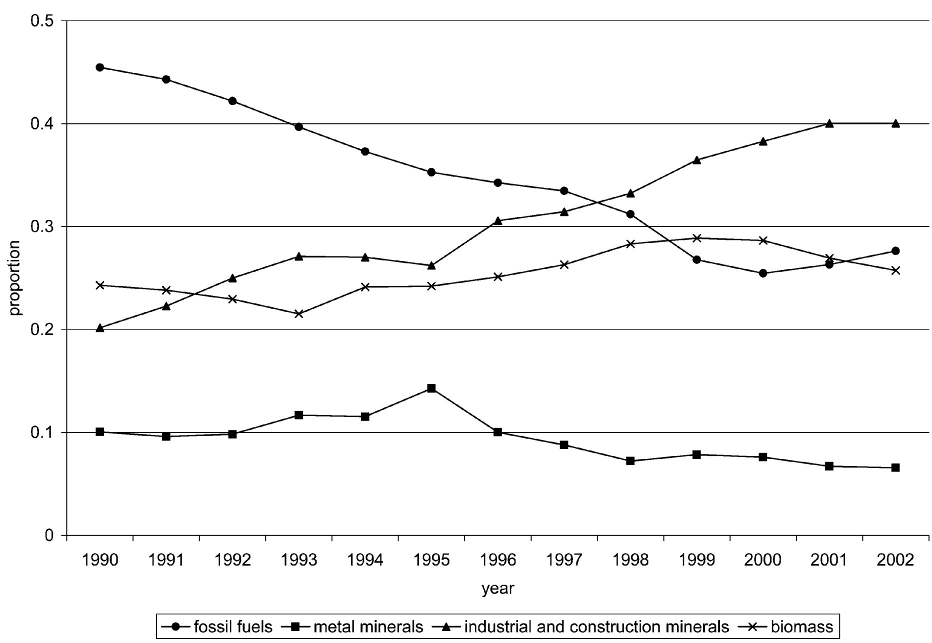

Figure 4 Proportions of direct material input (DMI) components for China from 1990 to 2002.

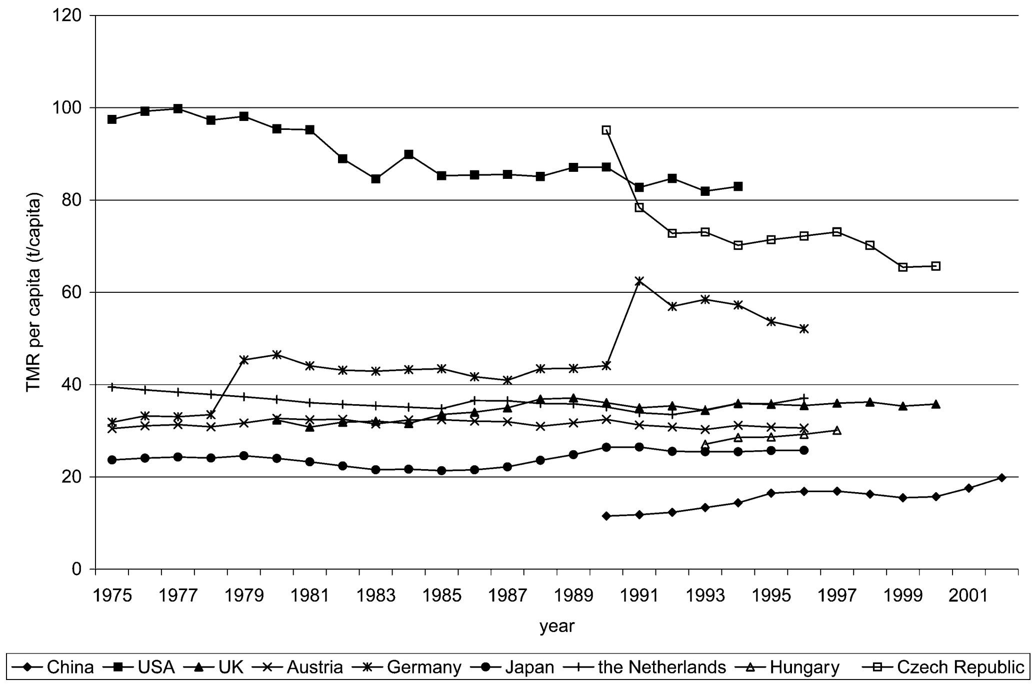

Figure 5 Total material requirement (TMR) for China and eight other countries, in tonnes per capita. *Sources:* Data for Austria, Germany, Japan, and the Netherlands (1975–1996): Matthews and colleagues (2000); for the Czech Republic (1990–2000): Ščasný and colleagues (2003); for Hungary (1993–1997): Hammer and Hubacek (2002); for the United Kingdom (1980–2000): Sheerin (2002); for the United States (1975–1994): Adriaanse and colleagues (1997).

period, which signifies that fossil fuels are an important material base of growth for a developing economy. This presented a variation pattern that was very similar to that of DMI or TMR (see figure 2), almost continuously increasing, with a slump around 1998. The amount of fossil fuels in DMI decreased from 1997 to 2000. During the same time, the net import of fossil fuels did not show a significant increase. The proportion of fossil fuels in DMI continued to decrease from 45.46% in 1990 to 25.46% in 2000, after which it began to increase again. At the same time, both the total amount and the growing relative proportion of industrial and construction minerals in DMI grew. After 1998, the proportion of industrial and construction minerals in DMI began to be greater than that of fossil fuels. Both the growing total amount and the growing relative proportion of industrial and construction minerals in DMI show their increasingly important role, which is also indicated by the corresponding extremely high growth rate of GDP in the construction industry—an annual average of 18.99%.

For TMR, the variation patterns of each component are almost the same as those for DMI. The difference is that the relative proportions of metal minerals and biomass are lower than those in DMI. It is clear that the UDE rates of fossil fuels and industrial and construction minerals are much higher than that of biomass. Furthermore, the total amount of metal minerals presented is lower than that of fossil fuels and industrial and construction minerals, so that the proportion is almost the same as that of biomass.

Figure 5 presents TMR per capita for China, and in comparison with eight countries, most of whose economies are industrialized. In China, TMR grew from 12 tonnes per capita (t/cap) in 1990 to 20 t/cap in 2002,[4] with an average annual increase of 4.62%. It can be seen in figure 5 that the TMR per capita in China is lower than that of all of the referenced countries.

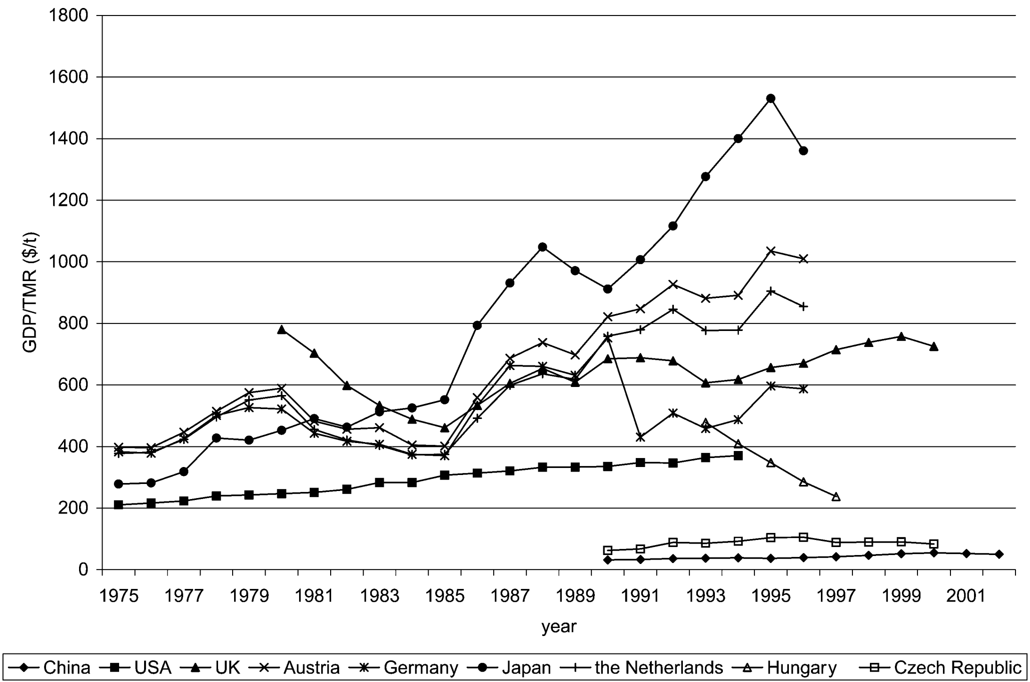

Figure 6 Gross domestic product per total material requirement (GDP/TMR) for China and eight other countries, in U.S. dollars per tonne (based on 2002 constant prices). *Sources:* Data for Austria, Germany, Japan, and the Netherlands (1975–1996): Matthews and colleagues (2000); for the Czech Republic (1990–2000): Ščasný and colleagues (2003); for Hungary (1993–1997): Hammer and Hubacek (2002); for the United Kingdom (1980–2000): Sheerin (2002); for the United States (1975–1994): Adriaanse and colleagues (1997).

During the same period, the annual population growth rate was only 0.98%, much lower than the annual growth rate of TMR per capita. This means that the rise of TMR per capita is not a direct result of population increase, but of the growth of the economy itself. Another consideration is that the material intensity, indicated by DMI per capita, is lower for China than for most other countries. The DMI per capita for China grew from 3 t/cap in 1990 to 6 t/cap in 2002; in comparison, the average DMI per capita for the European Union (EU-15) stayed around 17 t/cap from 1980 to 2000 (Eurostat 2002).

Figure 6 shows a comparison of GDP per TMR for China and for the other eight countries referenced in figure 5. GDP per TMR means the economic growth produced by 1 tonne of TMR materials, indicating the level of material efficiency. GDP per TMR for China grew from $32 U.S. per tonne (USD/t) in 1990 to 50 USD/t in 2002. It is clear that the material efficiency, indicated by GDP per TMR, of China is lower than that of any of the other referenced countries.

Considering the GDP per DMI, it can likewise be concluded that the material efficiency of China is much lower than the average level of Japan or the EU-15. GDP per DMI for Japan grew from 456 USD/t in 1975 to 2,188 USD/t in 1996 (Matthews et al. 2000). The average amount of GDP per DMI for the EU-15 grew from 490 USD/t in 1980 to 730 USD/t in 2000 (Eurostat 2002). By comparison, GDP per DMI for China grew from only 143 USD/t in 1990 to 178 USD/t in 2002 (see figure 7). When elements of the variation pattern of GDP per DMI for China are studied, there are four phases from 1990 to 2002: (a) from 1990 to 1993, the phase of growth to 158 USD/tonne in 1993; (b) from 1993 to 1995, the phase of decline to 148 USD/tonne in 1995; (c) from 1995 to 2000, regrowth to 191

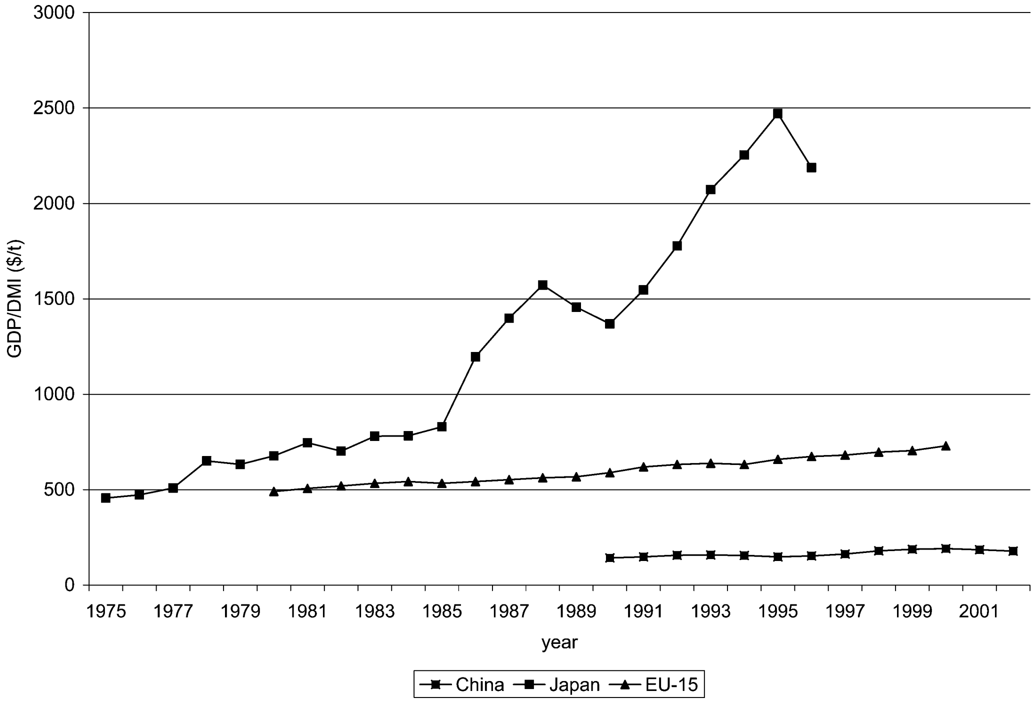

Figure 7 Gross domestic product per direct material input (GDP/DMI) for China, Japan, and the EU-15, in U.S. dollars per tonne (based on 2002 constant prices). *Sources:* Data for Japan (1975–1996): Matthews and colleagues (2000); for EU-15 (1980–2000): Eurostat (2002).

USD/t in 2000; (d) from 2000 to 2002, redecline to 178 USD/t in 2002. The variation patterns of GDP per TMR show the same trend as that of GDP per DMI, but to a lesser extent.

GDP per DMI or TMR can be used to indicate the material efficiency of an economy. Considering the points discussed above, it can be concluded that the material efficiency of China's economy is much lower than that of industrialized countries. Taking into account the continuous increase of China's GDP, the changes in material efficiency are mainly due to the changes in the total amount of material consumption.

Material Outputs

Material inputs are processed by the economic system and finally transformed into physical stocks in the economy and material outputs. DPO indicates the amount of materials emitted from domestic economic processes, being equal to dissipative flows plus emissions and wastes, the latter two of which can be grouped by gateway as emission to air, emission to water, and landfilled waste. Dissipative flows contain materials that are dispersed into the environment as a deliberate, or unavoidable (with current technology), consequence of product use. Output items and indicators for China are presented in table 3 and figure 8.

Oxygen drawn from the atmosphere during combustion processes is suggested by Eurostat (2001) to be a memorandum item for balancing. It is not included in the aggregated domestic extraction accounts, but is included in the aggregated output indicator DPO. Therefore, balancing items are needed for closing the materials balance and estimating NAS. In this study, DPO is calculated both including and excluding oxygen (see table 3). It can therefore be demonstrated that emission to air took a leading role amongst the components of DPO (see figure 8), in which the amount of emission to air did not include oxygen. Furthermore, the DPO for China has patterns of variation very similar to those of TMR and DMI. For example, both are rising and then slumping from 1998 to 2000, which shows

Table 3 Output items and indicators for China in petagrams (Pg)

Year	Dissipative flows	Emission to water	Landfilled waste	Emission to air: Including oxygen	Emission to air: Excluding oxygen	DPO: Including oxygen	DPO: Excluding oxygen	Exports
1990	0.03	0.02	0.05	2.43	0.68	2.53	0.77	0.12
1991	0.03	0.02	0.03	2.55	0.71	2.64	0.79	0.14
1992	0.03	0.02	0.03	2.68	0.74	2.76	0.82	0.16
1993	0.03	0.02	0.02	2.82	0.78	2.90	0.86	0.18
1994	0.03	0.02	0.02	2.99	0.83	3.07	0.90	0.25
1995	0.04	0.02	0.02	3.23	0.89	3.32	0.98	0.32
1996	0.04	0.02	0.02	3.37	0.93	3.45	1.01	0.34
1997	0.04	0.02	0.02	3.32	0.92	3.40	0.99	0.40
1998	0.04	0.02	0.07	3.15	0.87	3.28	1.01	0.39
1999	0.04	0.02	0.04	2.84	0.79	2.94	0.89	0.41
2000	0.04	0.02	0.03	2.80	0.78	2.90	0.87	0.53
2001	0.04	0.02	0.03	3.04	0.84	3.13	0.93	0.60
2002	0.04	0.02	0.03	3.54	0.98	3.63	1.07	0.70

Note: DPO = domestic processed output.

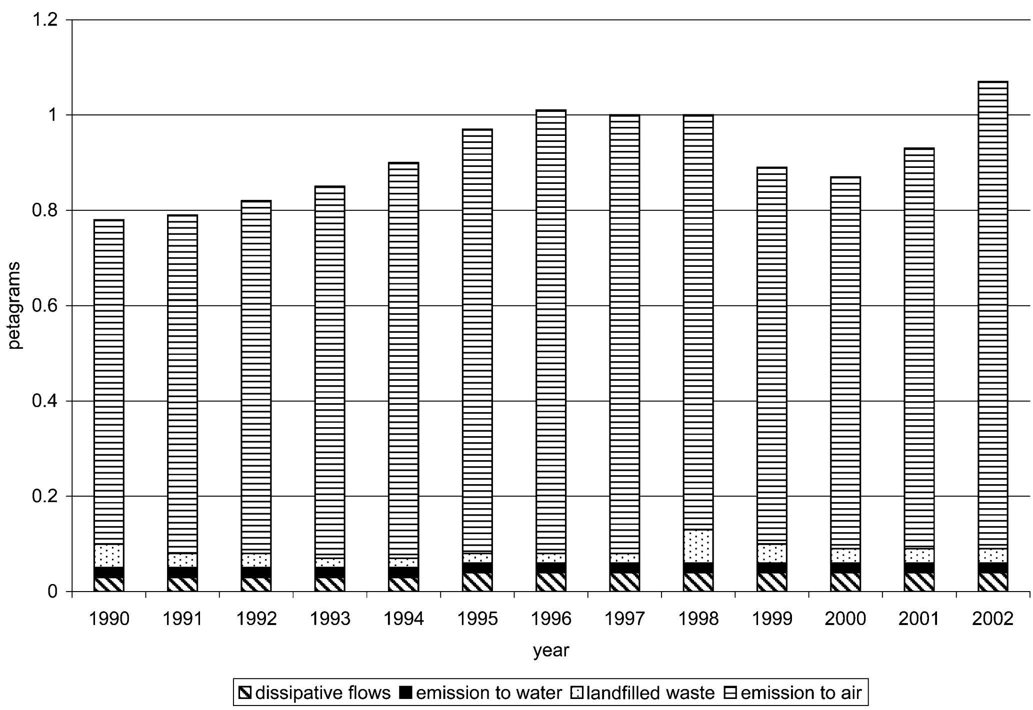

Figure 8 Components of domestic processed output (DPO) for China in petagrams. One petagram (Pg) = one billion tonnes (10^9 t) = 10^{12} kilograms (kg, SI) ≈ 1.102 × 10^9 short tons.

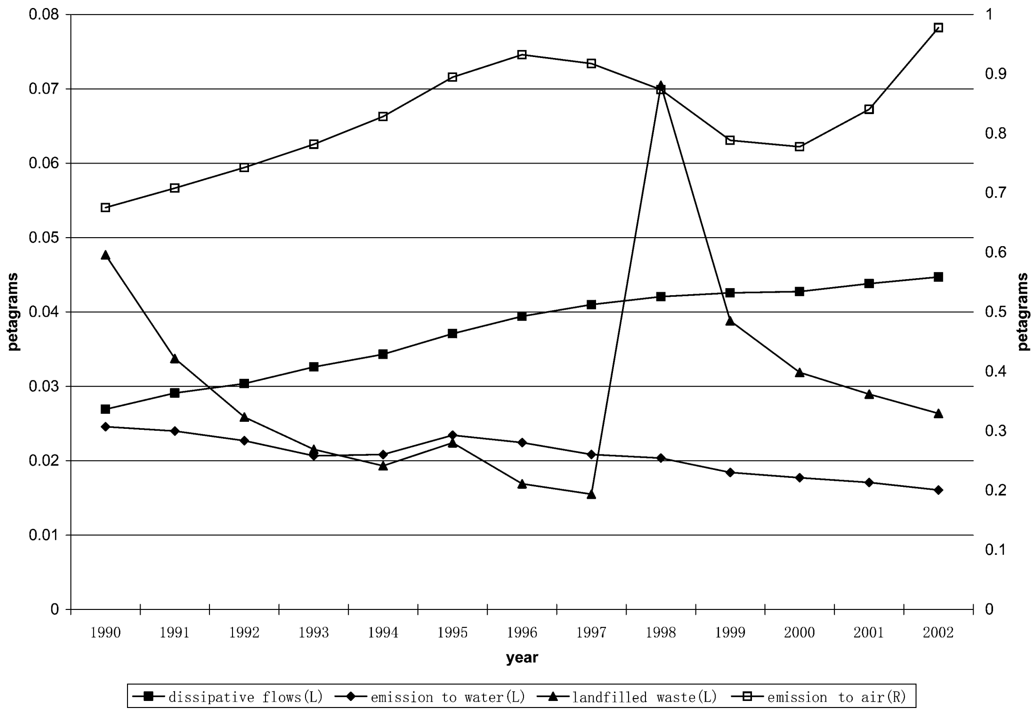

Figure 9 Patterns of variation of domestic processed output (DPO) components for China in petagrams.

that DPO has an approximately linear relationship with material input.

In figure 9, the far left-hand *y*-axis indicates dissipative flows, emission to water, and landfilled waste, whereas the far right-hand one indicates emission to air. It can be demonstrated that emission to air, excluding oxygen, also has the same variation pattern as material input indicators. It is solely due to the dominant proportion of emission to air that the DPO presents a variation pattern with a rise before a slump around 1998. Dissipative flows show a continuous increase from 1990 to 2002, which is mainly dominated by fertilizer used in agriculture. Emission to water and landfilled waste both decreased with only a small rise in each in 1995. Furthermore, landfilled waste also had a large rise around 1998. Although environmental problems in China today are much more serious than those in the past, it can be seen from the official statistical data that remarkable achievements have been attained in reducing emission to water and landfilled waste.

Physical Trade and Material Balances

Concerning international trade and environmental issues, the Physical Trade Balance (PTB) is an important indicator that expresses physical trade surplus or the deficit of the socioeconomy. In this context, surplus refers to net import (a positive number) of biophysical resources and deficit refers to net exports (a negative number). PTB is defined as the difference between imports and exports, which is equal to the result of subtracting exports from imports.

Figure 10 presents the quantities of imports, exports, and PTB for China from 1990 to 2002. Chinese physical trade with other countries, indicated by both imports and exports, increased from 1990 to 2002, with a slump in 1998. PTB first showed a decreasing deficit from 5 teragrams (Tg; one million tonnes) in 1990 to 1.81 Tg in 1992,[5] and then a decrease from a 45-Tg surplus in 1993 to a 54-Tg deficit in 1998, after which PTB presented an increasing physical surplus. In 2002 especially, the physical surplus for China

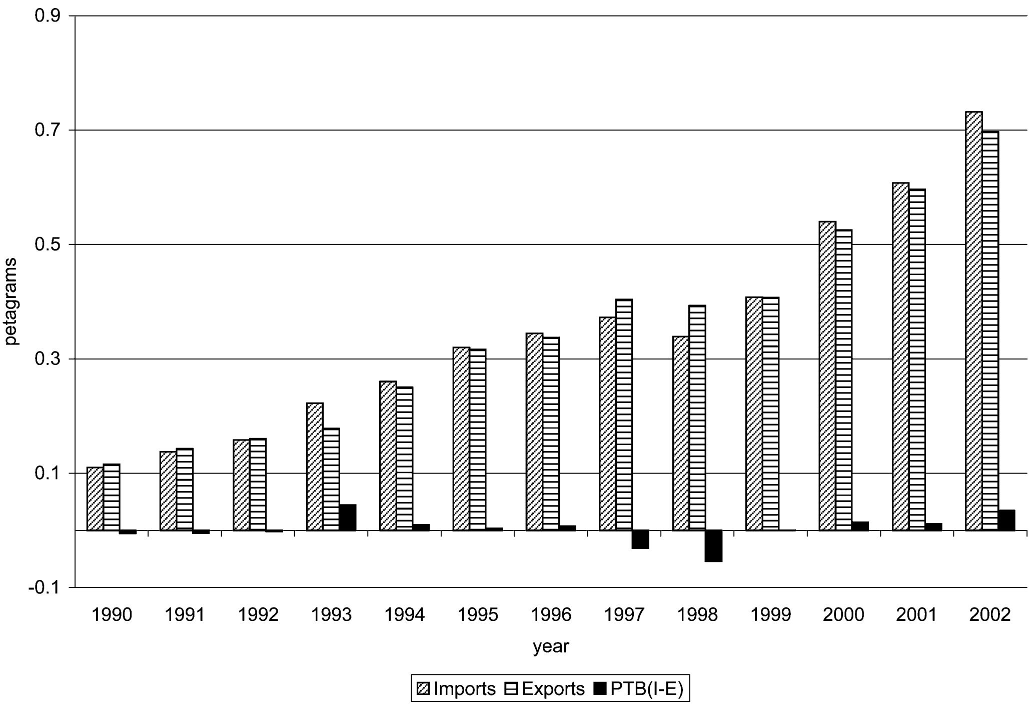

Figure 10 Imports, exports, and physical trade balance (PTB) for China, from 1990 to 2002, in petagrams.

increased sharply to about three times that of 2001. Similarly to most of the material input and output indicators, physical trade indicators also show interruption and slumping around 1998. When compared with European countries, the PTB per capita of China is much less than that of the EU-15. For example, in 2000, the PTB per capita of China was 0.01 tonnes per capita, whereas that of the EU-15 was 2.65 t/cap. The extremely low levels of physical trade per capita for China present an indication of very poor integration into the global market and of an early stage of industrialization. On the other hand, it can also be concluded that China's economy became increasingly active in the international market after 1999, which is shown by rapid growth of the quantity of physical trade.

Increased energy products (disaggregated) are important commodities contributing to the physical trade to and from China. In China there was a sharp increase in the export of coal from 17 Tg in 1990 to 90 Tg in 2001, which then began to drop again to 84 Tg in 2002. During the same period, the import of coal fluctuated around 2 Tg and then suddenly rose again to 11 Tg in 2002. Although the trade balance of coal presented a deficit in this period, the sharp growth of imports still shows a potential increase in the requirement for coal after 2002. Turning to the trade in crude oil and finished oil products, China's economy displayed high dependency on energy imports during the referenced period. The trade balance of crude oil changed from a deficit of 22 Tg in 1990 to a surplus of 62 Tg in 2002, whereas that of finished oil products changed from a deficit of 3 Tg in 1990 to a surplus of 10 Tg in 2002. The increasing physical surplus of energy materials for China presents a huge potential future requirement for energy products after 2002, especially for crude oil.

Material Consumption

Domestic material consumption (DMC) measures the total amount of material directly used in an economy. DMC equals DMI minus exports. Another important consumption indicator is net additions to stock (NAS), which measures the physical growth of the economy (Eurostat 2001). NAS indicates the quantity of new construction

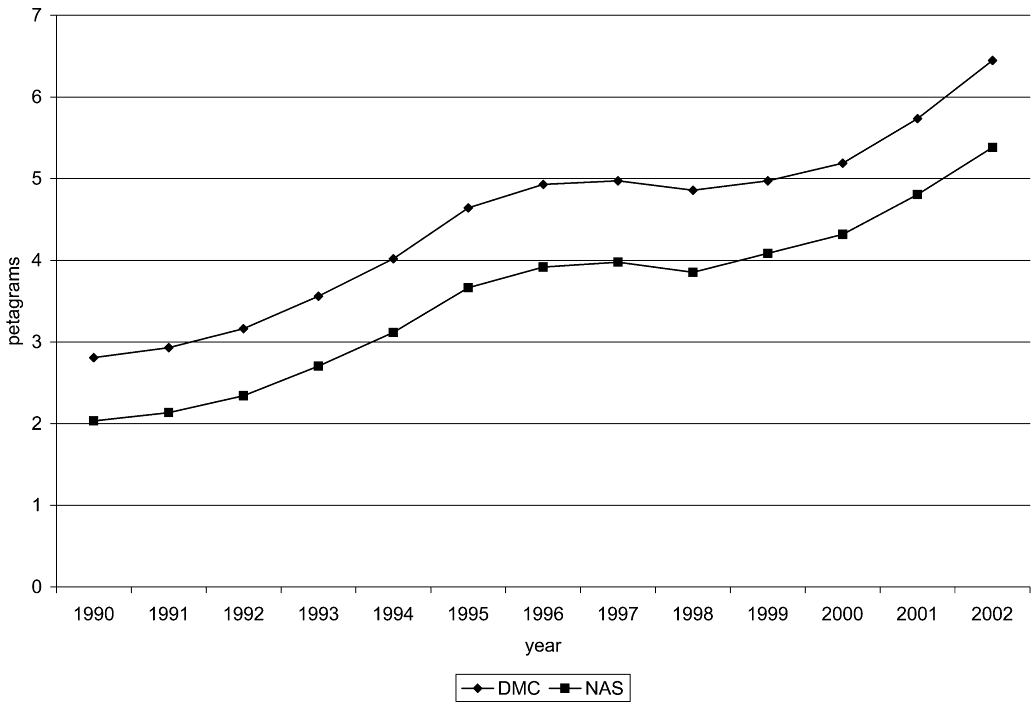

Figure 11 Domestic material consumption (DMC) and net addition to stock (NAS) for China from 1990 to 2002, in petagrams.

materials used in buildings and other infrastructure and materials incorporated into new durable goods.

Figure 11 presents the patterns of variation for DMC and NAS, which are approximately parallel. Except for slumps in 1998, the DMC and NAS both grew continuously from 1990 to 2002. The variation pattern is also similar to material input and output indicators discussed above.

Using the methodology of the IPAT model adapted by Eurostat (2002), environmental impact (I) is the product of population (P), affluence (A), and technology (T). In this study, DMC was chosen to represent environmental impact. Following is the IPAT equation:

DMC = (Population) × (GDP/Population) × (DMC/GDP).

Using this equation, a development situation can be studied over a certain period of time (see table 4). The first row of table 4 presents the development for the whole time period from 1990 to 2002. Demonstrated in this table is an average increase in the DMC of 7.17% per year, which is composed of a population growth of 0.98%, a GDP per capita growth of 8.68%, and an efficiency gain as demonstrated by DMC per GDP of 2.34%, which equals 1 minus the 97.66% growth of DMC per GDP. Other rows represent development for different periods. For example, during the period 1990–1995, the counteracting effect of higher efficiency—indicated by a DMC per unit of GDP of negative 1.26%—is overwhelmed by the growth of population (1.16%) and affluence (10.70%), causing increased consumption of material (10.57%). The data shown in table 4 were converted to comparable annual rates of change. For the periods 1990–1995 and 1998–2002, the IPAT annual rates of change can be used to describe the development of each period because the indicators during these periods continued changing in consistent trends.

Compared with the EU-15 from 1980 to 2000, the results presented in table 4 show a rapid growth of efficiency and affluence for China. For the period of 1990 to 2000, the EU-15 had an average annual efficiency growth of 2.1%,

Table 4 DMC = P × A × T annual percentage change from 1990 to 2002

Period	*DMC*	*Population*	*GDP/Population*	*DMC/GDP*
1990–2002	107.17%	100.98%	108.68%	97.66%
1990–1995	110.57%	101.16%	110.70%	98.74%
1995–1998	101.53%	100.99%	107.67%	93.37%
1998–2002	107.33%	100.73%	106.95%	99.63%

Note: DMC = P × A × T, or 107.17% = 100.98% × 108.68% × 97.66%, taking the period 1990–2002 for example. Percentages are all rounded. DMC = domestic material consumption; P = population; A = affluence; T = technology.

compared with 2.34% for China from 1990 to 2002. Due to the average annual growth of affluence in China (8.68%) being much higher than that of the EU-15 (1.9%), the growth of environmental pressure was still much higher than that of the EU-15, which, during the same period, showed a decline in environmental pressure. The annual population growth of China is nearly constant at around 1%. Because of the huge base, though, China needs to accept the consequences of population size, compared with an annual 0.3% growth of the EU-15 during the same period (Eurostat 2002).

Material Flow Balances

MFA provides an accounting framework for the physical dimensions of the economy. For example, figure 12 presents a sample material balance for China in 2002. The input side documents imported materials, raw materials extracted from the domestic economy, unused domestic extraction, and the air required for fossil fuel combustion and for human and animal respiration. Part of this material input stayed in the economy, and is shown as net addition to stock, such as infrastructure and durable goods. Within the domestic economy, there is also material recycled, which is not included in the material flow balance. On the output side, the rest of the materials are presented in the forms of exported material, waste disposal, dissipative flows, and emission to water and air. Such a material flow balance framework shows us the material components of an economy and gives us a comprehensive understanding of the whole system. Although data are available enough, this framework shows more details about the material flow balance of an economic system.

Trends of Material Indicators and Policy Discussion

Figure 13 presents the trends of economic, demographic, and material indicators for China from 1990 to 2002. Both the economic indicator GDP and the demographic indicator population kept increasing from 1990 to 2002, and all material indicators showed continuous growth with slumps in or after 1998. Within these slump periods, the nadirs of DMI, DMC, and NAS appeared in 1998, after which these three indicators began to grow again. TMR began to decrease in 1998, and its nadir appeared in 1999, after which it rose again. DPO decreased slightly earlier, in 1997, and its nadir appeared later, in 2000. During the period of the slump, DPO also increased slightly in 1998. Although DMI started to increase again in 1999, the nadir of TMR still appeared in 1999 because of the decrease of UDE during the same year. Similarly to TMR, the nadir of DPO in 2000 was due to the decrease of emission to air in 2000. Furthermore, the slight increase of DPO in 1998 was because of the sudden increase of landfilled waste.

Based on previous discussion, the trends of material input and output for China from 1990 to 2002 can be characterized as three-phased with one slump. The three phases are divided by the years 1995 and 2000. Behind the three phases, there are different macro policies that were implemented by the government. The time periods of these three phases very nearly match the Eighth, Ninth, and Tenth Five-Year Plans for National Economic and Social Development implemented by the Chinese central government. These three Five-Year Plans began, respectively, in 1991, 1996, and 2001, lasting for five years each. During the first period, the Eighth

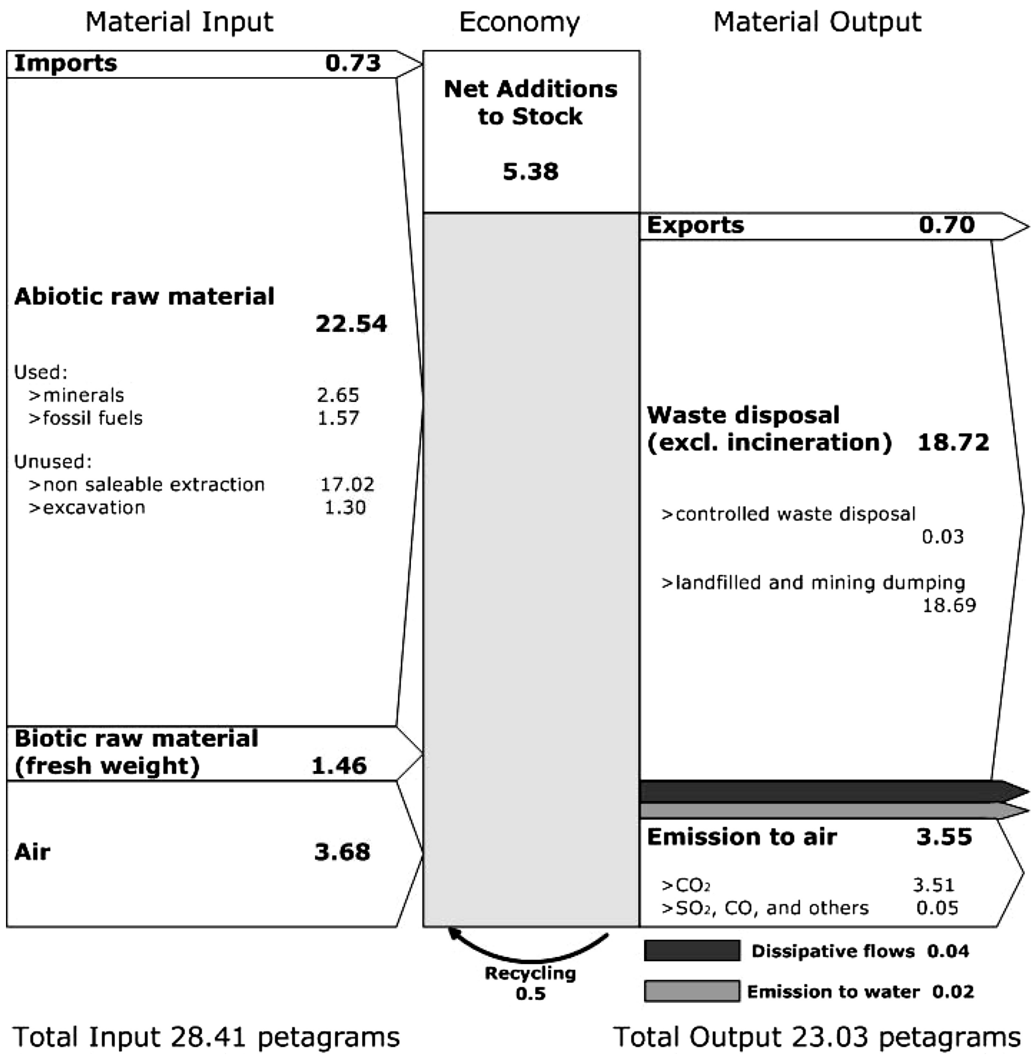

Figure 12 Material flow balance of China in 2002, in petagrams.

Five-Year Plan, the main task of China was to develop the infrastructure construction and foundational industries, such as energy, steel, construction materials, and petrochemicals. The rapid development of infrastructure construction led to increased material input and output. During the second phase, the Chinese government was making great efforts to shift the economic growth style from extensive to intensive. The rapid increase of investment was controlled in order to restrain the inflation rate. Those policy efforts made the economic system require and emit less material. After the beginning of the Tenth Five-Year Plan, the central government sustained the development of national economic growth, which greatly expanded China's domestic market. Its urbanization process also increased rapidly. During this phase the increase of material input and output was mainly caused by the rise in the DMI of industrial and construction minerals (see figure 4).

The slump occurred in or around 1998. At that time, the National Bureau of Statistics of China revised its industrial statistical framework. Its statistical confines were shrunken from corporations in towns to those in counties. The change induced a sudden slump of material input and output indicators around 1998. At the same time, the statistical framework of the State

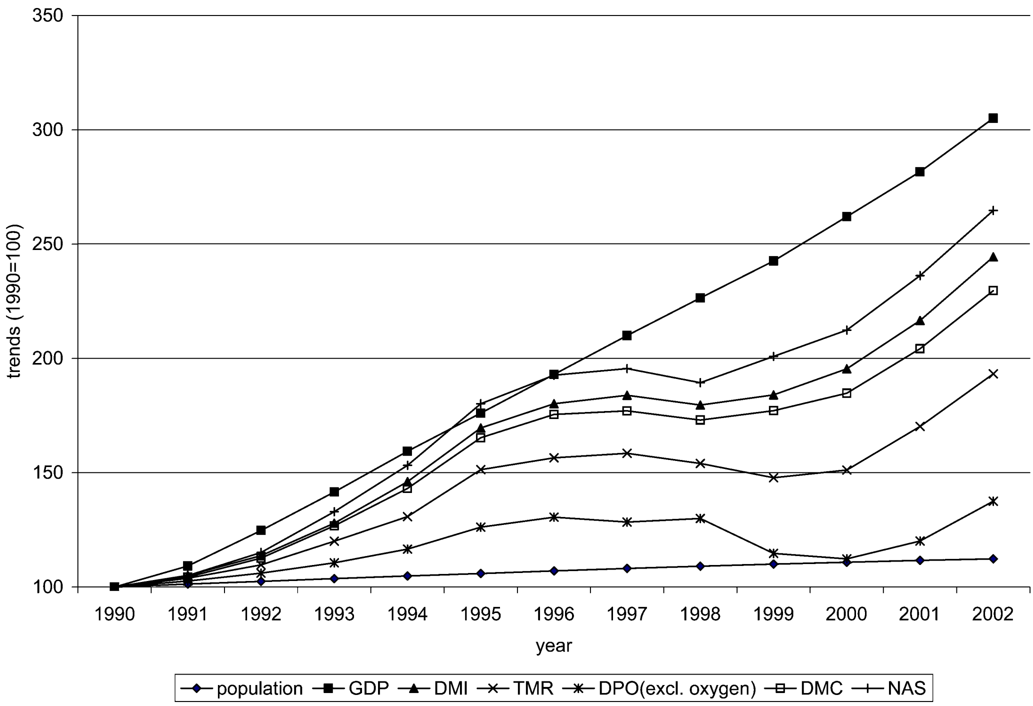

Figure 13 Trends of several macro indicators for China from 1990 to 2002, with 1990 = 100. GDP is based on 2002 constant prices. GDP = gross domestic product; DMI = direct material input; TMR = total material requirement; DPO = domestic processed output; DMC = domestic material consumption; NAS = net addition to stock.

Environmental Protection Administration of China was also revised. Its statistical confine of waste was expanded, which brought on the obvious increase in 1998 (see figure 9).

From 1990 to now, China has experienced great changes, which create possibly the most dynamic economy in the world. The physical dimensions of China's economy, which are measured by the EW-MFA method in this study, are sensitive to the macropolicy implemented by the central government. Although the statistical framework changed after 1998, the trends of EW-MFA indicators illustrate that materials required and wastes generated by China's economy increased parallel to economic growth. China's rapid economic growth was based on a tremendous requirement for natural resources.

Further Research

In the past decade, EW-MFA has been applied in most industrialized countries to describe the physical dimensions of the economy, which are regarded as one main research area of industrial ecology. Based on our experience, EW-MFA can show a macroscopic quantitative picture to describe the material flows occurring because of economic activities. Combined with other economic and social indicators, EW-MFA can also indicate the material efficiency of an economic system. The characteristics of aggregation of different qualities of material flows provide the possibility of a comparison of various physical flows. On the other hand, the advantage of aggregation is also its weakness, which has been criticized for a long time. Indicators that are too aggregated hide the different environmental impacts of different material flows; therefore, it is very difficult for the specific policies for solving environmental problems to be provided by the EW-MFA approach alone.

In the past few years, EW-MFA has developed very well as a tool in the field of industrial ecology. What lies in its future as a scientific tool? Two destinations are generally possible, one being to continue to develop its potential, and the other, to combine it with other tools. In our opinion, the future destiny of EW-MFA is the latter. EW-MFA has its own field of application, which describes the physical dimensions of an economy. After understanding the physical dimension, the next step is to choose other tools or develop new tools to make the economic system run more efficiently. To sum up, EW-MFA can be used as one of the pillars but it cannot be used to support a wide research field.

Turning to China's situation, physical data related to the economy, under the current national statistical framework, are not perfect. Therefore, in future research, more effort should be devoted to the investigation of the relationship between internal characteristics of the economy and the apparent material flow scene. Although improvement of the national statistical framework in China needs to be promoted, we do not suggest diving into the work of estimation and investigation to make the data more realistic, where a certain level of precision is already satisfied. In reflection of the internal characteristics of the economy, we suggest, first, a study of the structure of the economy and the level of technology. The structure of the economy could be represented by proportions of different economic sectors. For more comprehensive consideration, the physical input-output tables can also be useful, but are difficult to obtain. The level of technology could be represented by material consumption or emission per unit of economic growth or product manufactured. After the right indicators are found to represent the internal characteristics of the economy, a more detailed relationship between the economy and the environment can be presented to aid in decision making.

Conclusions

Since the strategy of reform and opening up was implemented in 1978, China has made great efforts to change its development strategy and to achieve modernization. Although the macroeconomic data show remarkable success, especially in the1990s, indicators measuring environmental pressures reveal a different picture. The amount of material consumption kept increasing almost continuously except for a slump around 1998, which was caused by a change in the statistical framework. Material consumption efficiency was influenced by the different macropolicy strategies of the Five-Year Plans.

In the past 15 years, the high rate of economic growth of China has basically rested upon the growth of a second sector and inhabitant consumption requirements. This growth has required a huge amount of natural resources, most of which were extracted from the domestic environment. Huge proportions of materials extracted led to huge waste and emissions, polluting the environment. In conclusion, there were huge environmental pressures and serious environmental pollution behind the compelling economic success of China in the 1990s. On the other hand, those environmental problems were unavoidable and may be ongoing for a certain period in the future for China, which has been suffering from the transition to industrialization.

From a long-term perspective on the physical dimension of China's economy discussed in this article, we know the patterns of variation, trends, absolute amounts, relative proportions, components, and efficiencies of physical input and output of China's economy. We have also deduced that the physical dimension indicators of the economy are more sensitive to different macropolicies than are the monetary indicators. Based on those results, relationships between physical indicators and characteristics of the economy need to be studied to support decision making.

As previously mentioned, EW-MFA can be regarded as a valuable method of painting the background picture to show the physical dimensions of the economy. In particular, EW-MFA can also provide fresh perspectives for developing China. But it is also illustrated that the EW-MFA methodology needs to be further developed in order to help in decision making. More specifically, emphasis should be given to the study of the relationship between physical dimensions and the inner characteristics of the economy.

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Notes

1. *China's Agenda 21—White Paper on China's Population, Environment, and Development in the 21st Century* was adopted at the 16th Executive Meeting of the State Council of the P.R. China on 25 March 1994.
2. When combined with MFA indicators, GDP and other monetary indicators need to be transformed into real GDP based on a constant price considering inflation and deflation.
3. One petagram (Pg) = one billion tonnes (10^9 t) = 10^{12} kilograms (kg, SI) ≈ 1.102 × 10^9 short tons.
4. One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons.
5. One teragram (Tg) = one million tonnes (10^6 t) = 10^9 kilograms (kg, SI) ≈ 1.102 × 10^6 short tons.

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