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Article

Development of the Physical Input Monetary Output Model for Understanding Material Flows within Ecological –Economic Systems

XU Ming

Brook Byers Institute for Sustainable Systems, Georgia Institute of Technology, Atlanta, GA 30332–0595, U.S.A.

Abstract: Input-output analysis (IOA) has been applied to study the integrated ecological-economic systems for decades. In this article, a physical input monetary output (PIMO) model is developed to aggregate economic systems with the associated ecological systems. The PIMO model utilizes economic information integrated in monetary input-output tables (MIOTs) and societal metabolism information provided by the method of material flow analysis (MFA). The fundamental process of applying PIMO model to practice is to make a PIMO table based on an existing MIOT. The computational framework of the PIMO model is then expressed by a set of mathematical correlations to represent mass balances of each economic sector and the entire economic system. Although there are four major categories of uncertainty in this approach, the PIMO model is relatively easy and sufficient to study an integrated national economic system and associated ecological system. A general algorithm of PIMO analysis is presented in this article and exampled with a case study on China's economy. In the case study, a PIMO table for China's economy is compiled with 43 economic sectors, 10 categories of resources, and 6 categories of wastes. Impacts on societal metabolism are studied by increasing final demands in different sectors. Each sector's influence on specific categories of resources or wastes is also studied by the PIMO model. Finally, the PIMO model is applied to evaluate a particular policy established by the Chinese central government. Results suggest that specific scenarios are suitable to achieve the predefined environmental goals.

Key words: input-output analysis; ecological-economic systems; monetary input-output table; material flow analysis; societal metabolism

1 Introduction

The fields of ecology and economics have been borrowing ideas from each other for a long time. Concepts in economics, such as producers and consumers, have been applied in ecological research from early twentieth century (Worster 1994). Principles of ecology have also been used to study the environmental issues for industrial and economic systems (Graedel *et al.* 1995; Ayres *et al.* 1996; Allenby 1999; Suh 2004b). Recently, it is generally agreed that the study of sustainability should pay special attention to the integrated ecological-economic systems which emphasize both physical aspects of the system, such as material or energy flows, and non-physical aspects, such as monetary or information flows.

Input-output analysis (IOA) is widely regarded as a powerful approach to illustrate the correlations among entities in ecological-economic systems, especially for national economies. Although there are various types of IOA applications on studying ecological-economic systems, the principles and theories are basically same and were first developed by Leontief (1936; 1941). Generally, there are two main areas in which IOA is applied to study ecological-economic systems. One is well-known as physical input-output tables (PIOTs) which present the input and output material flows in physical units for all sectors of an economic system (Kneese *et al.* 1970). The other application is mainly based on monetary input-output tables (MIOTs), which are used to present economic connections between economic sectors, with extensional information about physical interactions between the ecological system and the economic system (Suh 2005). In general, MIOT-related research has been applied more widely because its data availability is much better than PIOT-relat-

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The author: XU Ming. Email: Ming.Xu@gatech.edu.

ed research.

In this article, we first briefly summarize the previous research on ecological-economic systems using IOA methods. A model called physical input monetary output (PIMO) is then developed to integrate economic information in monetary units and societal metabolism information in physical units. A case study of PIMO application on China's economy is provided in the following section. Finally, discussions and future studies are concluded.

2 Input-output analysis on ecological-economic systems

The IOA model was first developed by Leontief in last century, and has been playing an important role in economic policy analysis. The basic input-output framework has two models, quantity model and price model. The quantity model can use either quantity units, such as tonnes steel or units of computers, or monetary units (Duchin 2004). The most widely used input-output model is in monetary units because of the feasibility of data collection and estimation, applicability to national economic accounting, and capability to balance by simple calculation. At present, MIOTs are available for a large number of countries as a part of their national account systems (Hubacek *et al.* 2003). The concept and computational structure of IOA, and the format of MIOTs can be referred to various well-known publications, such as Leontief (1966), Miller and Blair (1985), or United Nations (2003).

One of the main applications of IOA on ecological-economic systems is the compilation of PIOTs. The foundation of PIOT research was first made by Kneese *et al.* (1970). Examples of PIOTs published can be found in Kratterl and Kratena (1990); Kratena *et al.* (1992); Konijn *et al.* (1997); Stahmer *et al.* (1997); Pedersen (1999); Nebbia (2000); Stahmer (2000); Mäenpää (2002); and Hoekstra (2003). Based on the principles of IOA, PIOTs assemble physical data to present the materials exchanging among economic sectors. However, because of the relatively young history of physical input-output accounting, no standard method for the PIOT compilation has been developed yet. Therefore, existing PIOTs differ from each other in conventions and definitions more or less (e.g., Hubacek *et al.* 2003; Suh 2004a; Giljum *et al.* 2004; Weisz *et al.* 2006). The lack of standard compiling method is one of the main bottlenecks for PIOT application together with the difficulty of data collection.

The other main application of IOA to study ecological-economic systems extends MIOTs with mixed-unit data. In 1970, Leontief already introduced an input-output model to study the relationship between environmental pollution and economic structures by adding a row of pollutants and a column of anti-pollution in the conventional input-output table (Leontief 1970). Energy issues were widely discussed using IOA in 1970s (Hannon 1973; Bullard *et al.* 1975; Herendeen 1978). However, the method of IOA did not begin to attract broader attentions until in 1990s. To study the specific environmental impact of economic activities, Moriguchi *et al.* (1993) used input-output data to assess the life cycle carbon dioxide (CO_2) impacts of cars in Japan; Suh (2006) used IOA to study the impacts of economic activities on climate change from the perspective of structure characteristics; Hawkins *et al.* (2007) developed a mixed-unit model combining the methods of life cycle assessment (LCA) and material flow analysis (MFA) to track material flows and economic transactions throughout the economy; and the environmental input-output life cycle assessment (EIO-LCA) model developed at Carnegie Mellon University can quantitatively evaluate the environmental impacts of a product or service over the course of its entire life-cycle (Hendrickson *et al.* 2006). MIOTs are also modified with extended sectors to study the particular environmental issues, such as land use accounting (Hubacek *et al.* 2001), waste management (Nakamura *et al.* 2002; 2006), or environmental burdens caused by international trades (Peters *et al.* 2006a; 2006b; 2008; Weber *et al.* 2007). All these studies focused on particular environmental impacts or environmental impacts caused by particular economic activities. In this article, our approach differs from these studies since the entire ecological-economic system is quantitatively simulated in the PIMO model, but do not only consider specific environmental issues.

In the next section, the PIMO model is introduced, which is easy to implement using a relatively standard compilation framework. It also provides new tools for ecological economics, industrial ecology, and related fields.

3 Physical input monetary output model

The PIMO model focuses on an economic system which can be divided into various sectors. The surrounding ecological system has material exchanges with the economic system. In this section, the PIMO model is introduced in aspects of conceptual model, PIMO table, PIMO analysis, and uncertainty.

3.1 Conceptual model

A conceptual societal metabolism model of an ecological-economic system is illustrated as Figure 1. In the conceptual model, the economic system contains two sectors

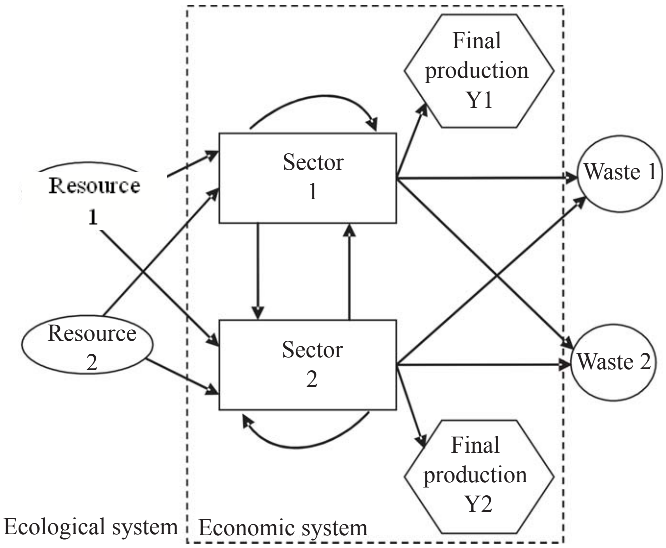

Fig. 1 The conceptual societal metabolism model of an ecological-economic system.

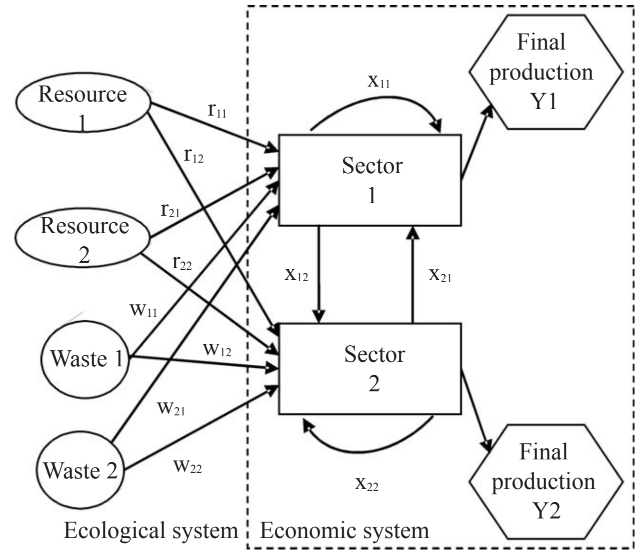

Fig. 2 The conceptual PIMO model.

each of which extracts two types of resources from the ecological system and emits two types of wastes to the ecological system. It should be specially stated that the term of "resource" means raw materials, such as mineral ores or crude oil, extracted directly from the ecological system by the economic system. On the other hand, the term of "waste" refers to the wastes and emissions generated by the economic sectors and returning to the ecological system without any further treatment. There is no economic cost for those materials in the conventional economic analysis including IOA.

The economic system can be modeled by IOA. Therefore, it is possible and reasonable to quantitatively represent the correlations between economic sectors by MIOTs and the connections between the ecological system and the economic system by the method of MFA.

To make the PIMO model easy to compile, the above conceptual model is modified as illustrated in Figure 2. In the conceptual PIMO model, wastes emitted by the economic system are regarded as "non-positive" (not only "negative" because specific types of wastes could be zero) inputs from the ecological system to the economic system, while resources are known as "positive" inputs. As a result, the conceptual PIMO model contains physical flows, both positive and non-positive, in the input side and monetary flows in the output side, which is also the reason why the model is described as physical input and monetary output model.

3.2 PIMO table

Based on MIOTs, extra rows can be added to extend to PIMO tables. Table 1 is the basic structure of the PIMO table. From top to bottom, the PIMO table can be divided into three parts. The first part is the conventional MIOT, which represents the structure of the economic system. The following part is the resource table and the last part is the waste table. The latter two parts represent the connection between the ecological system and the economic system. The classification of economic sectors and resource or waste categories in the PIMO table differs from research goals and available data. In general, it is easy to compile a PIMO table based on the MIOT classification of economic sectors which were already applied widely, especially for national economies, such as the system of national accounts (SNA) and the system of environmental and economic accounts (SEEA) provided by the United Nations (1993; 2003).

The symbols in the first part of the PIMO table are the same with those in MIOTs. Other symbols will be introduced thereafter together with basic computational framework of the PIMO model.

Consider that the ecological-economic system has n economic sectors, m categories of resources, and k categories of wastes. Let r_{ij} indicate the physical amount of the resource input from the category i to the sector j, where $r_{ij} \geqslant 0$. Therefore, le$R_i = \sum_{j=1}^{n} r_{ij} \geq 0$ measure the total amount of resource input to the economic system from the category i. Similarly, $w_{(m+i)j}$ indicates the physical amount of negative waste input from the category i to the sector j, which is actually the waste output from the sector j to the category i, where $w_{(m+i)j} \leqslant 0$. Thus, W_{m+i} can be used to represent

Table 1 The PIMO table.

Monetary Input		Monetary Output	Intermediate Monetary Output: Sector 1	2	…	n	Final Demand Y	Total Output X
Intermediate Monetary Input	Sector	1	x_{11}	x_{12}	…	x_{1n}	Y_1	X_1
		2	x_{21}	x_{22}	…	x_{2n}	Y_2	X_2
		…	…	…	…	…	…	…
		n	x_{n1}	x_{n2}	…	x_{nn}	Y_n	X_n
Value-added		V	V_1	V_2	…	V_n		
Total Input		X	X_1	X_2	…	X_n		
Physical Input			Physical Input Distribution: Sector					
Resource	Category	1	r_{11}	r_{12}	…	r_{1n}	R_1	
		2	r_{21}	r_{22}	…	r_{2n}	R_2	
		…	…	…	…	…	…	
		m	r_{m1}	r_{m2}	…	r_{mn}	R_m	
Waste	Category	m+1	$w_{(m+1)1}$	$w_{(m+1)2}$	…	$w_{(m+1)n}$	W_{m+1}	
		m+2	$w_{(m+2)1}$	$w_{(m+2)2}$	…	$w_{(m+2)n}$	W_{m+2}	
		…	…	…	…	…	…	
		m+k	$w_{(m+k)1}$	$w_{(m+k)2}$	…	$w_{(m+k)n}$	W_{m+k}	

the total amount of waste output from the economic system to the category *i*, where $W_{m+i} = \sum_{j=1}^{n} w_{(m+i)j} \le 0$.

The computational framework of PIMO model relies on mass balance of the entire economic system and each economic sector. To make the economic data, in monetary units, and the material data, in physical units, comparable, e_i, material intensity coefficient, is used to indicate the average weight of products of unit price in the sector *i*. For the sector *j*, the input contains material input from the ecological system, $\sum_{i=1}^{m} r_{ij} + \sum_{i=1}^{k} w_{(m+i)j}$, and the input from economic system, $\sum_{i=1}^{n} e_i x_{ij}$, where x_{ij} indicates the monetary input from sector i to sector *j*. The stocks and output of the sector *j* contain the output to other economic sectors, $e_j \sum_{i=1}^{n} x_{ji}$, and the final demand, $e_j Y_j$, where Y_j is the final demand of sector *j*. Therefore, the mass balance for a single economic sector can be expressed by the following equation, $\sum_{i=1}^{m} r_{ij} + \sum_{i=1}^{k} w_{(m+i)j} + \sum_{i=1}^{n} e_i x_{ij} = e_j(\sum_{i=1}^{n} x_{ji} + Y_j)$.

For the entire economic system, the input is materials from the ecological system, $\sum_{i=1}^{m} R_i + \sum_{i=1}^{k} W_{m+i}$. The stocks and output are final demands, $\sum_{i=1}^{n} e_i Y_i$. Thus, the mass balance of the entire economic system can be expressed as following, $\sum_{i=1}^{m} R_i + \sum_{i=1}^{k} W_{m+i} = \sum_{i=1}^{n} e_i Y_i$.

To mathematically present the computational framework of PIMO model, two coefficients are introduced. First, the intensities of resource consumption and waste generation in different sectors are indicated by the material efficiency coefficient which means the physical amount of materials in the resource or waste category *i* required to produce per unit economic output of the sector j,

$$p_{ij} = \begin{cases} \dfrac{r_{ij}}{X_j}, & i = 1, 2, \cdots, m \\ \dfrac{w_{(m+i)j}}{X_j}, & i = 1, 2, \cdots, k \end{cases}$$

where X_j is the total economic output of sector j. Second, the physical distribution of resources and wastes among economic sectors are presented by the material distribution coefficient

$$s_{ij} = \begin{cases} \dfrac{r_{ij}}{R_i}, & i = 1, 2, \cdots, m \\ \dfrac{w_{(m+i)j}}{W_{m+i}}, & i = 1, 2, \cdots, k \end{cases}$$

which means the portion of physical materials from the resource or waste category i to the sector j in the total input amount of that category of resource or waste to the entire economic system.

The detailed description of the computational framework of the PIMO model can be referred to the Supplementary Information.

3.3 PIMO analysis

The most important contribution of PIMO model is to make societal metabolism internalized in the modeling for the ecological-economic system. Resource consumption and waste generation are inherently connected with economic activities. Secondly, data required by the PIMO model are available and cheap for most important countries, which makes the model practical. Moreover, in the PIMO model, raw materials only go to the corresponding extraction sectors. Therefore, one only needs to know the total amounts of raw materials extracted and assign them to the corresponding extraction sectors, and does not need to allocate those amounts into all sectors because the information about sectoral resource consumption are expressed by the input-output correlations between the extraction sectors and other sectors.

In general, the PIMO model can be used to model the inherent relationship between material flows and economic flows. One can conduct the analysis by making one of the parameters exogenous. The performance of the system, both ecologically and economically, can be simulated from different aspects by changing one of those parameters. Particularly, the technical coefficient matrix, A, can indicate technology development of the economic system; the final demand vector, Y, can present the structural change; and the material efficiency matrix, $P=(p_{ij})_{(m+k)\times n}$, is the efficiency indicator of societal metabolism.

Figure 3 shows the general algorithm of the PIMO analysis. First, scenarios are set depending on research questions. Variables and constants are then chosen based on the scenarios. Then, the economic structure and material intensity coefficient are indicated, respectively, and material efficiency matrix and material distribution matrix are compiled. The model calculates the total resource required and waste generated by the economic-ecological system represented by corresponding scenarios. The scenarios are checked along each step by the constraints. Finally, further studies about the ecological-economic system are conducted based on the scenarios.

By using the PIMO model, one can compile a PIMO table based on an existing MIOT, and then study specific questions using selected parameters and mathematic correlations. This general analysis will be exampled in the following section by a case study for China's ecological-economic system.

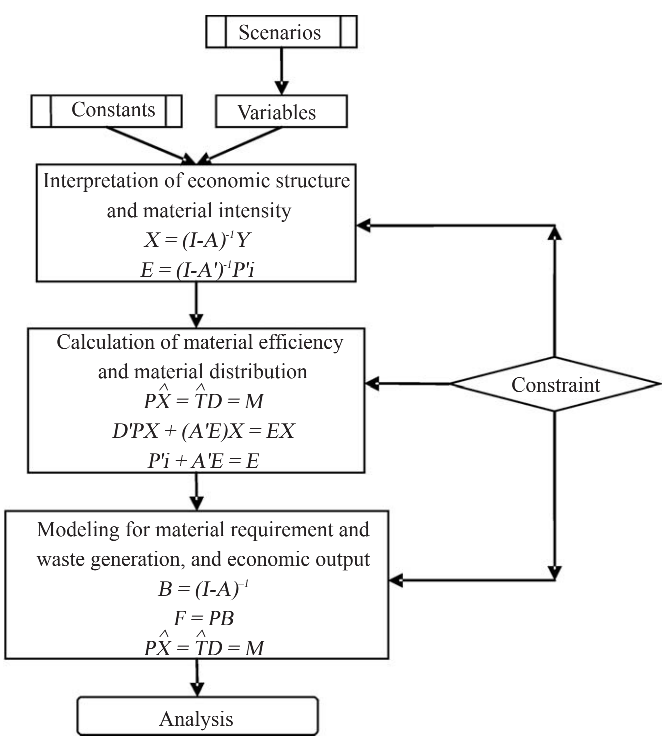

Fig. 3 The general algorithm of PIMO analysis.

3.4 Uncertainty

There are four major categories of uncertainty in the PIMO approach. First, economic input-output data are usually available only with a three or four-year time lag at best for most countries. Moreover, detailed economic input-output data are only compiled once in several years because of the costly procedure to obtain necessary information for a national economy, especially for large countries including China. Nonetheless, input-output data are still the cheapest and the most available source for national economy in terms of economic structure and technology development. Second, the endemic assumption of a linear relationship between societal metabolism and economic change is very common to all current input-output methods. Extra uncertainties are introduced when integrating physical data and monetary data together and converting monetary data into data with physical units based on this assumption. Without a doubt, the interaction between ecological and economic systems is far more complex than this at many different scales. Therefore, an important challenge for the future is developing more complete data sets and suitable methodologies, potentially based on some previous work such as dynamic input-output approach (Leontief *et al.* 1953), to enable more valid modeling of that complexity. Third, the assumption of homogeneous products in each sector is fundamental for input-output methods. The limitation due to this assumption can be improved by developing more data for subsectors without increasing the time lag too much. It is no doubtful that the disaggregation of economic sectors and material categories will significantly bring more uncertainties because the number of parameters is increased. However, it is also easier to improve the data quality for specific sectors or materials at smaller scales, which will reduce the uncertainties on the other hand. This task is particularly hard for the PIMO method because one needs to obtain both economic data and societal metabolism data. Last but not least, the uncertainty from the data themselves is also a major concern when doing uncertainty analysis. Various sources are available for data required in the PIMO method. However, only those whose uncertainty is relatively small or measurable could be chosen as the source of data. For a national economic system, as we will present in the case study section, data from the government' s statistical departments are relatively reliable and the most common source.

4 Case study

The PIMO model is designed to comprehensively, quantitatively, and systematically interpret the interaction between the ecological system and the economic system, but not isolatedly study specific resource-related or environmental issues. The sustainability issue in China is complicated and contains various aspects from resource scarcity to environmental pollutant (Liu *et al.* 2005; Cyranoski 2007). The continuously growing economy in China requires more resources and will cause more environmental problems. Moreover, those resource-related and environmental issues are all connected with each other. One single attempt on a specific aspect, for example, increasing efficiency in one specific sector in terms of energy consumption, can affect other sectors of the whole economy which will influence that sector reversely. Therefore, a comprehensive model is necessary for studying this complex system composing of various elements which are connected and related with each other in a complicated

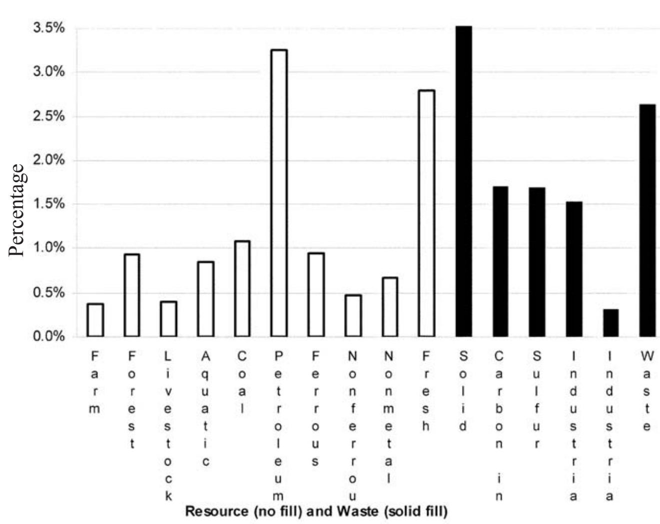

Fig. 4 Percentage changes of the total amounts of resources (no fill) and wastes (solid fill) associated with 10% increase of final demand in the Tertiary Industry.

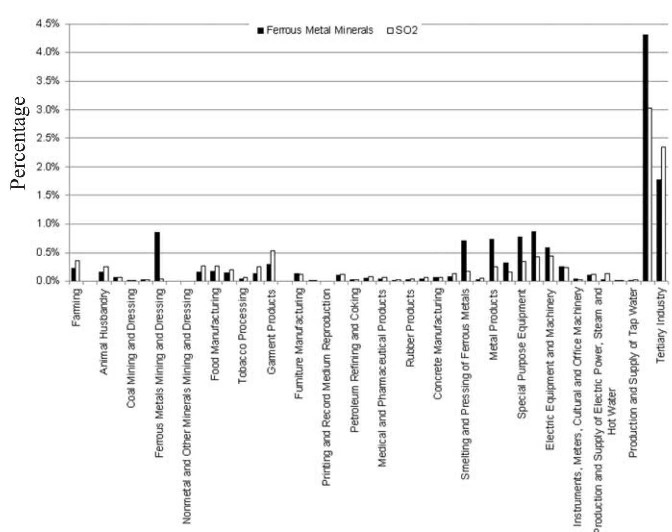

Fig. 5 Percentage changes of the total requirement for Ferrous Metal Minerals and the total generation of Sulfur Dioxide (SO_2) associated with 10% increase of final demand in one of the sectors.

pattern. The development of PIMO model meets this requirement and is especially suitable to comprehensively study the resource-related and environmental issues in China and the relation with its economic development.

In this section, the PIMO model is used to study China's ecological-economic system to illustrate the impacts on societal metabolism due to economic structure characters. A 2002 China PIMO model is assembled based upon 43 economic sectors which were aggregated from a 122-sector MIOT, 10 categories of resources, and 6 categories of wastes. Especially, the waste category of *Carbon in Carbon Dioxide* (*C in* CO_2) is used to balance the combustion process expressed by the reaction $C + O_2 \rightarrow CO_2$.

The economic input-output data were provided by the National Bureau of Statistics of China (NBSC) (2006), which also provided the societal metabolism data together with the Editing Committee of China Environmental Yearbook (2003); and Xu and Zhang (2007). Details about classification of economic sectors and materials and the model results can be referred from the Supplementary Information.

Based on the 2002 China PIMO table compiled, one can calculate material intensity coefficients for all sectors,

Table 2 Material intensity coefficients of the 2002 China PIMO model (tonnes per 2002 China yuan).

Material intensity coefficient	Sector
0.47	Farming
0.35	Forestry
0.30	Animal Husbandry
0.36	Fishery
1.71	Coal Mining and Dressing
0.70	Petroleum and Natural Gas Extraction
2.33	Ferrous Metals Mining and Dressing
2.10	Nonferrous Metals Mining and Dressing
2.65	Nonmetal and Other Minerals Mining and Dressing
0.45	Food Processing
0.62	Food Manufacturing
0.61	Beverage Manufacturing
0.20	Tobacco Processing
0.66	Textile Industry
0.64	Garment Products
1.24	Timber Processing, Bamboo, Cane, Palm Fiber and Straw Products
0.88	Furniture Manufacturing
1.16	Papermaking and Paper Products
0.97	Printing and Record Medium Reproduction
0.79	Cultural, Education and Sports Goods
1.03	Petroleum Refining and Coking
1.38	Raw Chemical Materials and Chemical Products
0.75	Medical and Pharmaceutical Products
1.16	Chemical Fiber
0.71	Rubber Products
1.04	Plastic Products
1.58	Concrete Manufacturing
1.18	Other Nonmetal Mineral Products
1.48	Smelting and Pressing of Ferrous Metals
1.51	Smelting and Pressing of Nonferrous Metals
1.21	Metal Products
0.98	Ordinary Machinery
0.96	Special Purpose Equipment
0.83	Transport Equipment
0.95	Electric Equipment and Machinery
0.71	Electronic and Telecommunications Equipment
0.84	Instruments, Meters, Cultural and Office Machinery
0.69	Other Machinery
6.34	Production and Supply of Electric Power, Steam and Hot Water
1.53	Production and Supply of Gas
3.70	Production and Supply of Tap Water
1.08	Construction
1.06	Tertiary Industry

as showed by Table 2. The sector 39, Production and Supply of Electric Power, Steam and Hot Water, has the highest material intensity coefficient, 6.34 tonnes per China yuan in 2002 price (similarly hereinafter). The sector 13, Tobacco Processing, has the lowest value, 0.20 tonnes per yuan. In general, the raw material extraction sectors and the sectors providing public utilities have higher material intensity coefficients than the manufacture sectors, service sectors, and agriculture sectors. As defined above, the material intensity coefficient measures the average weight of sectoral products with unit price.

To address the utility of the PIMO model compiled for China' s economic system, the impacts of economic growth on resource consumption and waste generation are studied. Taking the sector 43, Tertiary Industry, which contains all service sectors as the example, Figure 4 shows the percentage change of the total amounts of resources required and wastes generated due to a 10% increase of final demand in the sector 43. Solid waste is the most sensitive waste category influenced by this economic change due to the 3.89% increase, followed by wastewater with 2.63% growth. In the resource categories, the requirement for Petroleum and Natural Gas increases by 3.25% in the same scenario, followed by Fresh Water with 2.80% growth. Similar analysis can be conducted to see impacts on the societal metabolism due to other sectors' changes.

The total amounts of resources required or wastes generated associated with economic changes in different sectors are also studied by the PIMO model. As exampled by Ferrous Metal Minerals and Sulfur Dioxide (SO_2) in Figure 5, the 10% increase of final demand in one of sector will cause different percentage change of amounts of resources requirement or wastes generation. As expected, both ferrous metals required and SO_2 emitted are changed dramatically by Construction and Tertiary Industry because of huge demands of final consumption. The equipment manufacturing sectors and the sector of Ferrous Metals Mining and Dressing can also cause significant increase of ferrous metals requirements by growth of the sectroal final demand. For SO_2, the equipment manufacturing sectors also have important influences on the emission amount. The light industry sectors, such as Garment Products, and the agriculture sectors, such as Farming, consist of another main group of driving force for SO_2 emission. Similar analysis can also be conducted for other resources and wastes. Moreover, the results showed in Figure 5 can also be referred as an example of quantitatively sensitive analysis. For instance, the requirement of Ferrous Metal Minerals and the emission of SO_2 are more sensitive to the sectors of Construction and Tertiary Industry than to other sectors.

5 Conclusion

In this article, the application of IOA to study ecological-economic systems is reviewed. A new tool named PIMO model is developed based on the technique of IOA and the method of MFA to integrate ecological systems and economic systems. The PIMO model contains a set of parameters and mathematical correlations. The interaction between the ecological system and the economic system is regarded as the materials input from the former to the latter, which are quantified in physical units by MFA or related methods. The connection between economic sectors is modeled by MIOTs in monetary units. Mass balances of the entire economic system and each economic sector are compiled to quantitatively synthesize the complex ecological-economic systems. The material intensity coefficient is used to convert societal metabolism data in monetary unit to data in physical unit.

A case study of the PIMO analysis for China is presented. The 2002 PIMO table for China is compiled based on its 2002 MIOT. Necessary integration for economic sectors in MIOT is required to meet the availability of MFA data in the case of China in 2002. The PIMO table compiled contains 43 economic sectors, 10 resource categories, and 6 waste categories. Mass balances are built for each sector by the mathematical framework of the PIMO model. Studies for China' s ecological-economic system are conducted based on the PIMO table from the perspective of economic structure change.

The same as other IOA-related methods, data availability is the most difficult bottleneck to be conquered for compiling a PIMO table. While the development of IOA-related methods is attracting more and more attentions recently, much more effects should be put in the improvement for data availability. The most feasible way to improve data availability is to develop international standard for PIOTs or other national accounting frameworks focusing on not only economic systems but also ecological-economic systems. Moreover, the input-output methods have the linear correlation which simplified the complex ecological-economic systems. It helps to understand the complex system, though too much simplification may also lose a lot of information.

Future work should, where possible, focus on the analysis for structural characters of final consumption. Due to the lack of data, the Tertiary Industry, which contains final consumption sectors, is highly aggregated. The influences of final consumption on societal metabolism will be uncovered as more information is available for sub-sectors in the Tertiary Industry. Furthermore, significant improvement may be carried out on methodology development to study the impacts of products prices on societal metabolism.

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References

Allenby B. 1999. Industrial ecology: Policy framework and implementation. Upper Saddle River, New Jersey: Prentice Hall.

Ayres R, L Ayres. 1996. Industrial ecology: Towards closing the materials cycle. Cheltenham, UK: Edward Elgar.

Bullard C W, R A Herendeen. 1975. Energy cost of goods and services. *Energy Policy*, 3: 268–278.

Cyranoski D. 2007. China struggles to square growth and emissions. *Nature*, 446: 954–955.

Duchin F. 2004. Input-output economics and material flows. Rensselaer Working Papers in Economics. http://www.economics.rpi.edu/workingpapers/rpi0424.pdf

Editing Committee of China Environmental Yearbook. 2003. China environmental yearbook 2002. Beijing: China Statistics Press. (in Chinese)

Giljum S, K Hubacek, Sun L. 2004. Beyond the simple material balance: A reply to Sangwon Suh' s note on physical input-output analysis. *Ecol. Econ.*, 48: 19–22.

Graedel T, B Allenby. 1995. Industrial ecology. Upper Saddle River, New Jersey: Prentice Hall.

Hannon B. 1973. Structure of ecosystems. *J. Theor. Biol.*, 41: 535–546.

Hawkins T, C Hendrickson, C Higgins, H S Matthews, S Suh. 2007. A mixed-unit input-output model for environmental life-cycle assessment and material flow analysis. *Environ. Sci. Technol.*, 41: 1024–1031.

Hendrickson C, L Lave, H S Matthews. 2006. Environmental life cycle assessment of goods and services: An input-output approach. Washington, DC: Resources for the Future.

Herendeen R A. 1978. Input-output techniques and energy-cost of commodities. *Energy Policy*, 6: 162–165.

Hoekstra R. 2003. Structural change of the physical economy: Decomposition analysis of physical and hybrid input-output tables. Free University of Amsterdam, the Netherlands: Ph.D. dissertation.

Hubacek K, S Giljum. 2003. Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecol. Econ.*, 44: 137–151.

Hubacek K, Sun L. 2001. A scenario analysis of China's land use and land cover change: Incorporating biophysical information into input-output modeling. Struct. *Change Econ. Dynam.*, 12: 367–397.

Konijn P, S de Boer, J van Dalen. 1997. Input-output analysis of material flows with application to iron, steel and zinc. Struct. *Change Econ. Dynam.*, 8: 129–153.

Kratena K, A Chovanec, R Konechy. 1992. Eine ökologischer volkswirtschaftliche Gesammtrechnung für Österreich. Die Umwelt Input Output Tabelle 1983. Vienna, Austria: Institut für sozial-, wirtschafts- und umweltpolitische Forschung. (in German)

Kratterl A, K Kratena. 1990. Reale Input-output Tabelle und ökologischer Kreislauf. Heidelberg, Germany: Physica-Verlag. (in German)

Kneese A, R Ayres, R d'Arge. 1970. Economics and the environment: A material balance approach. Baltimore, Maryland: The John Hopkins Press.

Leontief W. 1936. Quantitative input and output relations in the economic system of the United States. *Review of Economic Statistics*, 18(3): 105–125.

Leontief W. 1941. The structure of American economy, 1919–1939: An empirical application of equilibrium analysis. New York: Oxford University Press.

Leontief W. 1953. Studies in the structure of American economy. New York: Oxford University Press.

Leontief W. 1966. Input-output economics. New York: Oxford University Press.

Leontief W. 1970. Environmental repercussions and the economic structure: An input-output approach. *Rev. Econ. Stat.*, 52: 262–271.

Liu J, J Diamond. 2005. China's environment in a globalizing world. *Nature*, 435: 1179–1186.

Mäenpää I. 2002. Physical input-output tables of Finland 1995: Solutions to some basic methodological problems. The Fourteenth International Conference on Input-Output Techniques, Montreal, Canada, October 10–15.

Miller R, P Blair. 1985. Input-output analysis: foundations and extensions. Upper Saddle River, New Jersey: Prentice Hall.

Moriguchi Y, Y Kondo, H Shimizu. 1993. Analysing the life cycle impacts of cars: The case of CO_2. *Industry and Environment*, 16: 42–45.

Nakamura S, Y Kondo. 2002. Input-output analysis of waste management. *J. Ind. Ecol.*, 6: 39–64.

Nakamura S, Y Kondo. 2006. A waste input-output life cycle cost analysis of the recycling of end-of-life electrical home appliances. *Ecol. Econ.*, 57: 494–506.

National Bureau of Statistics of China. 2006. China input-output table 2002. Beijing: China Statistics Press. (in Chinese)

Nebbia G. Contabilità monetaria e contabilità ambientale. *Economia Pubblica*, 2000; 30: 5–33. (in Spanish)

Pedersen O. 1999. Physical input-output tables for Denmark, products and materials 1990, air emissions 1990-1992. Copenhagen, Demark: Statistics Denmark.

Peters G, E Hertwich. 2006a. Structural analysis of international trade: Environmental impacts of Norway. *Econ. Sys. Res.*, 18: 151–181.

Peters G, E Hertwich. 2006b. The importance of imports for household environmental impacts. *J. Ind. Ecol.*, 10(3): 89–109.

Peters G, E Hertwich. 2008. CO_2 embodied in international trade with implications for global climate policy. *Environ. Sci. Technol.*, 42: 1401–1407.

Stahmer C. 2000. The magic triangle of input-output tables. In: Simon S, J Proops (eds). Greening the accounts. Cheltenham, UK: Edward Elgar.

Stahmer C, M Kuhn, N Braun. 1997. Physische Input-output Tabellen, Beiträge zu den Umweltökonomischen Gesamtrechnungen, Band 1. Stuttgart, Germany: Metzler-Poeschel Verlag. (in German)

Suh S. 2004a. A note on the calculus for physical input-output analysis and its application to land appropriation for international trade activities. *Ecol. Econ.*, 48: 9–17.

Suh S. 2004b. Functions, commodities and environmental impacts in an ecological-economic model. *Ecol. Econ.*, 48: 451–467.

Suh S. 2005. Theory of materials and energy flow analysis in ecology and economics. *Ecol. Modell.*, 189: 251–269.

Suh S. 2006. Are services better for climate change? Environ. *Sci. Technol.*, 40: 6555–6560.

United Nations. 1993. System of national accounts 1993. United Nations Statistics Division, http://unstats.un.org/unsd/sna1993/toctop.asp.

United Nations. 2003. Handbook of national accounting: Integrated environmental and economic accounting 2003. United Nations Statistics Division, http://unstats.un.org/unsd/envaccounting/seea2003.pdf.

Weber C, H S Matthews. 2007. Embodied environmental emissions in U.S. international trade, 1997-2004. *Environ. Sci. Technol.*, 41: 4875–4881.

Weisz H, F Duchin. 2006. Physical and monetary input-output analysis: What makes the difference? *Ecol. Econ.*, 57: 534–541.

Worster D. 1994. Nature's economy: A history of ecological ideas. 2nd ed. Cambridge, UK: Cambridge University Press.

Xu M, Zhang T. 2007. Materials flow and economic growth in developing China. *J. Ind. Ecol.*, 11(1), 121–140.

Appendices

Appendix A: Parameter definitions

- n, m, k: the ecological-economic system has n economic sectors, *m* categories of resources, and *k* categories of wastes;

- x_{ij}, a_{ij}, b_{ij}, A, X_i, Y_i, V_i: parameters from IOA and MIOTs;
- r_{ij}: the physical amount of resource input to sector *j* from resource category *i*, $r_y \geqslant 0$;
- R_i: the total amount of input to the economic system from resource category *i*, $R_i = \sum_{j=1}^{n} r_{ij} \geq 0$;
- $w_{(m+i)j}$: the physical amount of waste output from sector *j* to waste category *i*, $w_{(m+i)j} \leqslant 0$;
- W_{m+i}: the total amount of output from the economic system to waste category *i*, $W_{m+i} = \sum_{j=1}^{n} w_{(m+i)j} \leq 0$;
- e_i: material intensity coefficient, the average weight of products per unit price in the sector *i*;
- E: material intensity vector, $E=(e_1, e_2,\cdots,e_n)^T$
- p_{ij}: material efficiency coefficient, the physical amount of materials from resource or waste category *i* required to produce per unit of economic output of sector *j*,

$$p_{ij} = \begin{cases} \dfrac{r_{ij}}{X_j}, & i = 1, 2, \cdots, m \\ \dfrac{w_{(m+i)j}}{X_j}, & i = 1, 2, \cdots, k \end{cases}$$

- P: material efficiency matrix, $P=(p_{ij})_{(m+k)\times n}$;
- s_{ij}: material distribution coefficient, the portion of physical materials input from resource or waste category *i* to sector *j* in the total input amount of that category of resource or waste to the entire economic system,

$$s_{ij} = \begin{cases} \dfrac{r_{ij}}{R_i}, & i = 1, 2, \cdots, m \\ \dfrac{w_{(m+i)j}}{W_{m+i}}, & i = 1, 2, \cdots, k \end{cases}$$

- S: material distribution matrix, $S=(s_{ij})_{(m+k)\times n}$;
- G: $(m+k)\times 1$ vector of total amount of materials input, including m types of resource and *k* types of waste, $G=(R_1, R_2,\cdots,R_m, W_{m+1}, W_{m+2},\cdots,W_{m+k})^T$;
- $M = \begin{Bmatrix} (r_{ij})_{m\times n} \\ (w_{(m+i)j})_{k\times n} \end{Bmatrix}_{(m+k)\times n}$ is $(m+k)\times n$ matrix of material consumption;
- f_{ij}: material cumulative input coefficient, $f_{ij} = \sum_{t=1}^{n} p_{it} t_{tj}$;
- $T=(t_{ij})_{n\times n}=(I-A)^{-1}$ is the cumulative input matrix;
- F: $(m+k)\times n$ matrix of cumulative material requirements, both positive and negative.

Appendix B: Computational framework

Consider that the ecological-economic system has n economic sectors, m categories of resources, and k categories of wastes. Let r_{ij} indicate the physical amount of the resource input from the category *i* to the sector *j*, where $r_y \geqslant 0$. Therefore, let $R_i = \sum_{j=1}^{n} r_{ij} \geq 0$ measure the total amount of resource input to the economic system from the category *i*. Similarly, $w_{(m+i)j}$ indicates the physical amount of negative waste input from the category *i* to the sector *j*, which is actually the waste output from the sector *j* to the category *i*, where $w_{(m+i)j} \leqslant 0$. Thus, W_{m+i} can be used to represent the total amount of waste output from the economic system to the category *i*, where $W_{m+i} = \sum_{j=1}^{n} w_{(m+i)j} \leq 0$.

The intensities of resource consumption and waste generation in different sectors are indicated by the material efficiency coefficient which means the physical amount of materials in the resource or waste category *i* required to produce per unit economic output of the sector *j*,

$$p_{ij} = \begin{cases} \dfrac{r_{ij}}{X_j}, & i = 1, 2, \cdots, m \\ \dfrac{w_{(m+i)j}}{X_j}, & i = 1, 2, \cdots, k \end{cases}$$

where X_j is the total economic output of sector *j*. $P=(p_{ij})_{(m+k)\times n}$ represents the material efficiency matrix.

The physical distribution of resources and wastes among economic sectors are presented by the material distribution coefficient

$$d_{ij} = \begin{cases} \dfrac{r_{ij}}{R_i}, & i = 1, 2, \cdots, m \\ \dfrac{w_{(m+i)j}}{W_{m+i}}, & i = 1, 2, \cdots, k \end{cases}$$

which means the portion of physical materials from the resource or waste category *i* to the sector *j* in the total input amount of that category of resource or waste to the entire economic system. $D=(d_{ij})_{(m+k)\times n}$ indicates the material distribution matrix.

From the definition of the material efficiency matrix and the material distribution matrix, the relationship between P and D can be expressed as

$$P\hat{X}=\hat{T}D=M \tag{1}$$

where $X=(X_1, X_2,\cdots, X_n)^T$ is $n\times 1$ vector of total economic outputs; $T=(R_1, R_2,\cdots,R_m, W_{m+1}, W_{m+2},\cdots,W_{m+k})^T$ is $(m+k)\times 1$ vector of total materials inputs, including m types of resources and *k* types of wastes (negative); $M = \begin{Bmatrix} (r_{ij})_{m\times n} \\ (w_{(m+i)j})_{k\times n} \end{Bmatrix}_{(m+k)\times n}$ is $(m+k)\times n$ matrix of material consumption; and hat (^) diagonalizes a vector.

The mass balance for the entire economic system can be expressed by

$$\sum_{i=1}^{m} R_i + \sum_{i=1}^{k} W_{m+i} = \sum_{i=1}^{n} e_i Y_i$$

where e_i, ecological-economic coefficient (e-coefficient), indicates the average weight of products of unit price in the sector i; and Y_i is the final demand of sector i. The left-hand-side (LHS) of the equation presents net physical amount of the material inputs to the economic system, while the right-hand-side (RHS) is the physical value of the monetary outputs (final demand). Rewrite the mass balance equation into the matrix format,

$$iPX = E'Y \quad (2)$$

where $i=(1,1,\cdots,1)$ is $1\times(m+k)$ unit vector; $Y=(Y_1, Y_2,\cdots, Y_n)^T$ is $n\times1$ vector of final demand; and $E=(e_1, e_2,\cdots, e_n)^T$ is $n\times1$ vector of e-coefficients.

Consider each sector as a control system, and derive mass balance for the sector j,

$$\sum_{i=1}^{m} r_{ij} + \sum_{i=1}^{k} w_{(m+i)j} + \sum_{i=1}^{n} e_i x_{ij} = e_j\left(\sum_{i=1}^{n} x_{ji} + Y_j\right)$$

where x_{ij} indicates the monetary input from sector i to sector j. The LHS of the equation is the summation of the material inputs to the sector j from categories of resources and wastes (negative), and other economic sectors, and the RHS is the output summation from the sector j. The RHS can be rewritten as $e_j(\sum_{i=1}^{n} x_{ji} + Y_j) = e_j X_j$. Therefore, the mass balance of sector j can be expressed as

$$\sum_{i=1}^{m} r_{ij} + \sum_{i=1}^{k} w_{(m+i)j} + \sum_{i=1}^{n} e_j x_{ij} = e_j X_j$$

Rewrite the sectoral mass balance equation into the matrix format as

$$D'PX + (\hat{A'E})X = \hat{E}X \quad (3)$$

where A is n×n technical coefficient matrix.

From the definition of material efficiency coefficients, one can get,

$r_{ij}=x_j p_{ij}$, $(i=1,2,\cdots,m)$;

$w_{(m+i)j}=x_j p_{(m+i)j}$, $(i=1,2,\cdots,k)$

Substitute the above equations into the sectoral mass balance equation and derive

$$\sum_{i=1}^{m} X_j p_{ij} + \sum_{i=1}^{k} X_j p_{(m+i)j} + \sum_{i=1}^{n} e_i a_{ij} X_j = e_j X_j$$

where $a_{ij} = x_{ij} / X_j$ represents the technical coefficients. Rewrite the equation above by canceling X_j in both RHS and LHS,

$$\sum_{i=1}^{m} p_{ij} + \sum_{i=1}^{k} p_{(m+i)j} + \sum_{i=1}^{n} e_i a_{ij} = e_j$$

and the matrix format is

$$P'i + A'E = E \quad (4)$$

where $i=(1,1,\cdots,1)^T$ is $(m+k)\times1$ unit vector. Equation (3) and equation (4) are both derived from the sectoral mass balance equation. Thus they are equivalent from each other. However, equation (4) is much easier for effective computation because it does not need the material distribution matrix D which is required in equation (3). From equation (4), one can calculated e-coefficients based on the technical matrix and the material efficiency matrix,

$$E = (I-A')^{-1}P'i \quad (5)$$

Similar with IOA, there are also cumulative effects in the PIMO model for the physical inputs. Define f_{ij} as the material cumulative input coefficient, which means the cumulative net material input of category i caused by per unit of output of sector j. f_{ij} can be calculated as

$$f_{ij} = \sum_{t=1}^{n} p_{it} b_{tj}$$

where b_{ij} is the cumulative input coefficient. Rewrite the above equation to matrix format as

$$F = PB \quad (6)$$

where $F=(f_{ij})_{(m+k)\times n}$ is the matrix of cumulative material requirements, and $B=(b_{ij})_{n\times n}=(I-A)^{-1}$ is the cumulative input matrix.

Appendix C: Sector and material classifications

Table S1 Classification of sectors in China's economic system.

No.	Sector	No.	Sector
1	Farming	7	Ferrous Metals Mining and Dressing
2	Forestry	8	Nonferrous Metals Mining and Dressing
3	Animal Husbandry	9	Nonmetal and Other Minerals Mining and Dressing
4	Fishery	10	Food Processing
5	Coal Mining and Dressing	11	Food Manufacturing
6	Petroleum and Natural Gas Extraction		

Continued table S1

12	Beverage Manufacturing	28	Other Nonmetal Mineral Products
13	Tobacco Processing	29	Smelting and Pressing of Ferrous Metals
14	Textile Industry	30	Smelting and Pressing of Nonferrous Metals
15	Garment Products	31	Metal Products
16	Timber Processing, Bamboo, Cane, Palm Fiber and Straw Products	32	Ordinary Machinery
		33	Special Purpose Equipment
17	Furniture Manufacturing	34	Transport Equipment
18	Papermaking and Paper Products	35	Electric Equipment and Machinery
19	Printing and Record Medium Reproduction	36	Electronic and Telecommunications Equipment
20	Cultural, Education and Sports Goods	37	Instruments, Meters, Cultural and Office Machinery
21	Petroleum Refining and Coking	38	Other Machinery
22	Raw Chemical Materials and Chemical Products	39	Production and Supply of Electric Power, Steam and Hot Water
23	Medical and Pharmaceutical Products		
24	Chemical Fiber	40	Production and Supply of Gas
25	Rubber Products	41	Production and Supply of Tap Water
26	Plastic Products	42	Construction
27	Concrete Manufacturing	43	Tertiary Industry

Table S2 Classification of resources and wastes.

No.	Material
A	Farm Crops
B	Forest Products
C	Livestock Products
D	Aquatic Products
E	Coal
F	Petroleum and Natural Gas
G	Ferrous Metal Minerals
H	Nonferrous Metal Minerals
I	Nonmetal Minerals
J	Fresh Water
K	Solid Waste
L	Carbon in Carbon Dioxide (C in CO2)
M	Sulfur Dioxide (SO2)
N	Industrial Soot
O	Industrial Dust
P	Waste Water

利用物质投入价值产出模型分析生态经济系统的物质流

徐 明

佐治亚理工学院Brook Byers可持续系统研究所，佐治亚州，GA 30332-0595，美国

摘要：利用经济投入产出表所提供的经济数据以及物质流分析所提供的社会代谢数据，建立了物质投入价值产出(PIMO)模型对生态经济系统的代谢进行量化分析。该模型基于一系列经济部门的物质平衡方程，可以较为方便地对生态经济系统的物质代谢进行模拟和分析。以中国为例，本文对该模型的建立和使用进行了演示，各类经济活动对生态经济系统代谢的影响得到了量化。

关键词：投入产出分析；生态经济系统；价值投入产出表；物质流分析；社会代谢